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State of workability design technology for fresh concrete in Japan

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Abstract

As high-performance concrete and various new types of concrete, such as self-compacting concrete and anti-washout underwater concrete, have been developed and put to practical use, it has become increasingly important to optimize the consistency of fresh concrete to attain high-quality and efficient concrete construction, which is called workability design of concrete. Up to the present, many scientists from all parts of the world have performed a lot of studies on the rheological properties, test method, and flow analysis of fresh concrete for realizing the workability design under various construction conditions. This paper gives a brief outline of the current situation, problems and prospects in the art of workability design of fresh concrete in Japan.

Keywords: A. Fresh concrete; A. Workability; A. Rheology; E. Modeling; Flow analysis

1. Introduction

In order to make concrete construction high-quality and efficient, fresh concrete should have suitable consistency to answer to the environment and the structure and construction conditions of constructed building member, including environmental temperature, member shape, density of reinforcing bars, and carrying, compaction and finishing methods, etc. With technology advances in chemical and mineral admixtures, desirable consistency of fresh concrete can be easily realized. In response to the recent changes in structure condition and construction method of concrete member, including an increase in density of reinforcing bars in high reinforced concrete (RC) building or earthquake-resistant RC building, wide use of pump carrying method, improvement in pumper's capacity, and non-vibration construction, etc., the concrete having high fluidity and suitable viscosity has been developed and increasingly used, such as self-compacting concrete (SCC). It has become insufficient to use the slump test to characterize consistency of new types of concrete, and the consistency set empirically is likely to not meet the actual demands. Therefore, workability design of concrete has become necessary, which is a process of optimizing concrete's consistency to be well adapted for certain structure and construction conditions, the establishment of rheological test method and workability design technology is an extremely important problem awaiting solution in fresh concrete sphere.

An inexpensive and efficient workability design is to predict and further optimize the workability of concrete by flow simulation for the selected construction processes, e.g. transportation, casting, compaction, finishing, etc. Clarifying and modeling the rheological behaviors of fresh concrete, and establishing a suitable flow analysis method are the most basic conditions of workability design, as shown in Fig. 1 [1,2].

Because the rheological behaviors of high-fluidity concrete are relative simple in comparison with ordinary one, the Bingham model is approximately applicable. Hence, high-fluidity concrete makes the workability design more necessary, it also provides a good opportunity to develop and use the workability design technology because its self-compacting characteristic can simplify the flow simulation.

Japanese scientists in the concrete sphere have performed a lot of studies on the rheology of fresh concrete from early times. Since Y. Tanigawa and H. Mori proposed the concept and method of workability design of concrete in 1988 [1,2], the objective and problems necessary to be solved became clear for the study of concrete rheology, A great deal of effort has been put into the studies on rheological models, test methods, and

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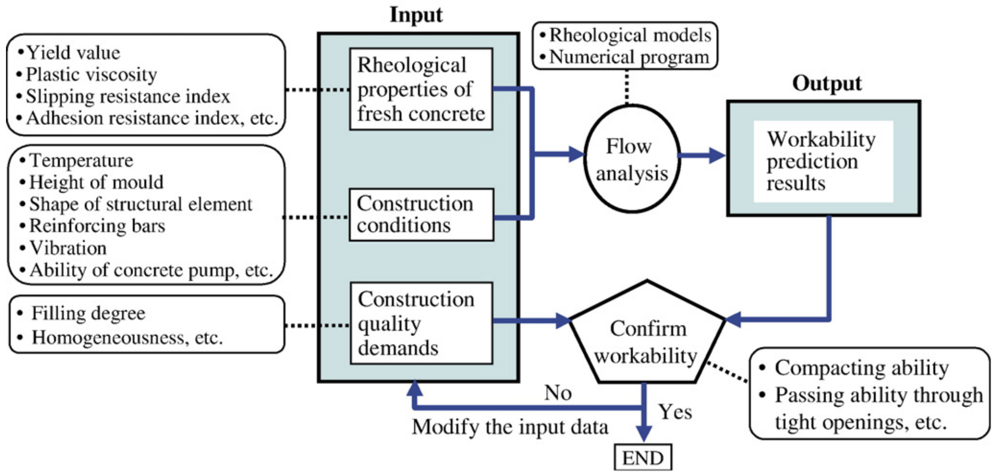

Fig. 1. Workability design based on numerical flow analysis.

theoretical and computer-aided numerical flow analyses, etc. of fresh concrete for developing the workability design technology in the past near 20 years in Japan. This paper introduces the current state of the art in workability design of concrete in Japan, enumerates the problems facing scientists at the forefront of technology developments of consistency evaluation and flow analysis, and outlines the prospects in this research area by identifying what aspects are difficult, and what information is still insufficient for workability design.

2. Advances in the development of workability design technology

Workability design should be carried out based on the information of flow situation during cast, which is obtained from flow analyses or cast experiments of concrete under given structure and construction conditions. It is obvious that the flow analysis, whether it is in theory or computer-aid numerical analysis, does not need enormous labor and materials consumed in the cast experiments. Since workability prediction is a key to the workability design, the advances in the workability prediction technology are closely relevant to those in the development of workability design of concrete. The current state of the arts in flow analysis and workability prediction in Japan is first described in the following.

2.1. Workability prediction

The flow analyses of fresh concrete reported in Japan are classified as shown in Table 1. Almost all the flow analyses have taken the concretes having flow ability as objects of study. Unfortunately current flow analysis technology cannot yet predict precisely the flow behaviors of any concrete mixture in various construction process under any given structure and construction conditions.

One of the main causes of this situation is the severe shortage of numerical input information for the flow analysis, including rheological properties of concrete, structure and construction conditions, etc . The Bingham Model is generally employed to roughly describe the deformation characteristics of fresh concrete. Because of this bold simplification, the flow analysis based on this model yields rough results about flow behaviors. The numerical flow analysis can roughly predict how wide a range in a mould concrete will fill [12,19]. However, the predictions are generally more demanded for the flow in extremely small-scale spaces, such as confirmations of filling state in mould corner, flow ability through tight opening formed by steel bars, and the segregation state of coarse aggregate in fresh concrete.

Obviously, in order to precisely and numerically predict the workability of any kind of concrete, it is necessary to use a

Table 1
Categories of reported flow analyses

Object of analysis	Theoretical analysis	Numerical analysis
Mixing	Probabilistic investigation on mixing degree [3]	Mixing process of concrete using mixer [4]
Pumping (fluidity in pipe)	Flow in pump pipe caused by deformation and slipping [5]	Blocking in tapered pump pipe [4]
		Flow in bent pump pipe [8]
	Pressure loss in tapered pump pipe [6]	Pulsation of pump [9]
	Pressure loss in bent pump pipe [7]	Upward flow in pipe under vertical pressure of pump [9]
Casting	Passing behaviors between reinforcing steel bars [10]	Casting upward in steel pipe column from the bottom by pump pressure [11]
	Earlier flow of matrix mortar due to concrete segregation [10]	Casting in a wall mould having steel bars [12]
Compaction	Propagation of vibration [13]	Propagation of vibration [16]
	Emission of Air in concrete due to compaction [14]	Flow behaviors under vibration [16]
	Increase behaviors in fluidity under vibration [15]	Settling behaviors of coarse aggregates in the fresh concrete [17]
	Dragging-ball test under vibration [15]	
Lateral pressure	Lateral pressure of mould when concrete is in a standstill state [18]	Lateral pressure of mould when concrete is being cast [18]

Table 2
The flow analyses of consistency tests

Object of flow analysis	Theoretical analysis	Numerical analysis
Usual consistency tests	Slump test [20,23]	Slump test [4,21,28]
		Flow test [21,28]
	Flow test [26]	L-flow test [29,30]
		Funnel test [17]
	Funnel test [27]	VB test [16]
Other consistency tests	Inclined pipe test [31]	Steel bars-placed box test [4]
		Vibrated box test [16]
		Shear box test [33]
Rheological tests	Rotational viscometer [34]	Rotational viscometer [37]
	Dragging-ball viscometer [35]	Dragging-ball test [21]
	Parallel plate viscometer [36]	Parallel plate viscometer [21]

finer rheological model than the Bingham model. Accurate evaluation of fresh concrete's properties, quantification and numerical expression of structure and construction conditions, and suitable numerical calculation method are also essential.

2.2. Analysis of consistency test method

The flow analyses, which take various consistency tests of fresh concrete as objects of study as shown in Table 2, are the most up to now, and have achieved many satisfactory results [e.g., 20,21,29]. This is of course because the boundary conditions of these flow analyses are simpler than those in actual construction, so accurate results are easily produced by relatively simple calculations. These flow analyses can greatly help to understand the physical meanings of the consistency tests. It is also thought that these flow analyses have led the way to establish a real flow simulation technology for actual concrete construction, because they can confirm the validity of input data and calculation methods [22].

The greatest numbers of the flow analyses have been about slump test, including theoretical analysis [e.g., 20,23] and numerical analysis [e.g., 21], and have already produced a lot of useful results. However, the slumping behaviors of fresh concrete are not yet completely reproduced by the flow analyses. For instance, the flow analysis, based on the Bingham model, can not simulate the collapse behavior of upper concrete during slump test as shown in Fig. 2 [24].

Since the flow of fresh concrete after the slump cone was pulled up is very similar to that when fresh concrete is being cast, the slump test may be considered as a model experiment that simplifies actual concrete construction process — casting. If the analytical technique and the rheological model of fresh concrete are established, by which the slumping behaviors of any kind of concrete can be completely reproduced, it is likely that actual construction simulation and workability prediction will become reality.

3. Rheological models

The rheological model is a key to the flow analysis of fresh concrete. It may determine what analytical technique is well applicable, what indexes can properly characterize concrete's rheological properties, and further what functions the used rheological test apparatus of concrete must have. A complex model may result in a complicated measurement of rheological properties, but numerical and detailed input of the rheological properties may simplify the numerical calculation and improve the precision of flow analysis. At present, it can be said that the inactivity in the flow analysis and in the workability prediction is mainly due to the lack of proper rheological models applicable widely to various fresh concrete. In the following section, the state and research trends of rheological models of fresh concrete in Japan are introduced.

3.1. Model describing deformation resistance under static stress

The Mohr–Coulomb yield condition is sometimes used to predict the limit stress of shear failure for dry concrete [25]. This model was once used to analyze the lateral pressure of fresh concrete on the mould [38]. The constants of this model are inter-friction angle and adhesive stress, as shown in Eq. (1).

$$\tau = \sigma_n \tan\phi + C. \quad (1)$$

where τ is shear stress; σ_n is normal stress; ϕ is inter-friction angle; and C is adhesive stress.

Obviously the deformation behaviors of fresh concrete cannot be expressed by the Mohr–Coulomb model. Thus, the deformation and flow of fresh concrete is traditionally described by the Bingham model, which has two constants — yield value and plastic viscosity, as shown in Eq. (2), supposing that fresh concrete is a kind of homogeneous, continuous body.

$$\tau = \eta\dot{\gamma} + \tau_y \quad (2)$$

where $\dot{\gamma}$ is shear rate; η is plastic viscosity; and τ_y is yield stress.

The rheological behaviors of high fluidity concrete may be approximated with the Bingham model, but the application of this linear model to ordinary concrete is unreasonable.

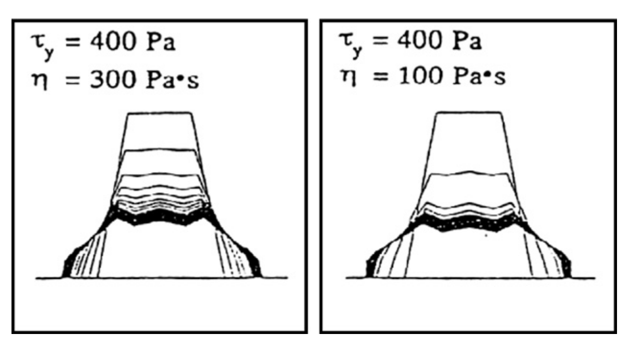

Fig. 2. Examples of slump test simulation.

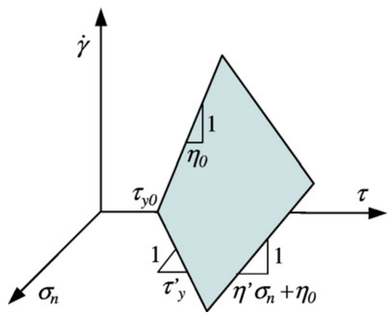

Fig. 3. Combined rheological model of fresh concrete.

According to the author's theoretical investigation [43], even for high fluidity concrete, the relation between shear rate and shear stress is linear only in the lower shear rate range, whereas in the higher shear rate range, approaches an exponential relationship.

The experiments [25,32] indicated that the so-called Bingham constants of fresh concrete are not constants, and vary with vertical pressure. That is to say, the deformation resistance is dependent on applied vertical pressure. The author's investigation by a microscopic approach clarified that the yield or failure condition of cement-based materials in the fresh state is formally the same as that of the Mohr–Coulomb model, as shown in Eq. (3). The yield stress or the limit stress of shear failure thus increases linearly with normal stress on the shear plane [39,56].

$$\tau_y = \sigma_n \tan(\theta + \phi) + (C_w + C_v) \quad (3)$$

where θ is mean value of particle contact angles between particle contact planes and maximum shear plane; C_w is shear resistance caused by surface tension of mixing water; and C_v is cohesive resistance caused by moving cement particles.

Based on the experimental results of the deformation' s dependence on vertical pressure stated above, Mori and Tanigawa [32] proposed a new rheological model for fresh concrete, as shown in Fig. 3. This model is a combination (called combined rheological model) of the Mohr–Coulomb model and the Bingham model, and thus can express the deformation's dependence on stress state. This combined model has four parameters to characterize the deformation properties of fresh concrete as shown in Eq. (4). However, because the measurement of the four rheological constants isn't easy, and there have been only a few measurement examples, the combined rheological model is not yet widely accepted as a universal model.

$$\tau = \dot{\gamma}(\eta_0 + \eta'\sigma_n) + (\tau_{y_0} + \tau'_y\sigma_n) \quad (4)$$

where η_0 and τ_{y0} are initial plastic viscosity and initial yield stress, respectively, when $\sigma_n = 0$; and η' and τ'_y are proportional constants.

The deformation behaviors of fresh concrete are also influenced by other many factors besides stress state, including stress duration, stress history, loading speed, loading rate, scale of available deformation space, temperature, elapsed time after mixing, etc. [48,49,56,57]. A new rheological model has been expected to consider generally the effects of these factors, thus it may be more complex than the combined model.

The premise of using the Bingham model is to consider fresh concrete as homogenous, continuous material. Actually, fresh concrete is not a continuous material, and has the dual characteristics of liquid and granular material. Thus, it may be necessary to construct the rheological model of fresh concrete from a standpoint of discontinuous body and by a theoretical approach due to having no rheological test method accepted widely.

The author [43,58] has proposed a micro-structural model for fresh concrete, which considers fresh mortar/concrete as a kind of particle assembly containing water, as shown in Table. 3. Like other loose materials, e.g. unconsolidated soil and sand, the shear deformation of fresh concrete shifts from a visco-elastic-plastic stress state to a shear failure state with increasing shear stress (visco-elastic state is ignored). The higher the fluidity of fresh concrete, the smaller its limit stress (peak stress). The weight of high fluidity concrete itself may cause its deformation to directly enter the shear failure state. The flow behaviors of high fluidity concrete, which the Bingham model describes, are considered to be those in its shear failure state [58].

On the basis of the proposed micro-structural model, the author has clarified the flow mechanism of cement-based materials in the fresh state by expanding the Eyring's rate process theory [43,59], and quantified the moving behaviors of the particles in the fresh concrete by a probabilistic investigation [60]. Furthermore, the flow curve equation of high fluidity concrete [43], and the constitutive equation of fresh concrete in visco-plastic stress state [60] are induced by theoretical analyses. The flow curve equation of high fluidity concrete is as shown in Eq. (5). This microscopic approach has initially

Table 3
Micro-structure model of fresh concrete — Particle assembly model

Composition		Features	
Mixing water	Adhering on the surfaces of particles or filling in the pores of particle assembly. Water content affects interparticle frictional angles, adhesion forces on particles' surfaces, etc.		
Cement grains	Cohesive particles	In standstill state	Being subjected to inter-frictional resistance and dilatancy-causative resistance.
		In moving state	Being subjected to inter-frictional resistance, dilatancy-causative resistance and cohesive resistance.
Aggregates grains	Cohesionless particles	Being always subjected to inter-frictional resistance and dilatancy-causative resistance.	

shown a potential to clarify quantitatively the rheological properties of various types of fresh concrete.

$$\dot{\gamma} = c_1 \exp\left(-\frac{E_c}{kT}\right)\sinh[c_2(\tau - \tau_y)] \quad (5)$$

where E_c is mean potential energy of cement particles; k is Boltzmann's constant; T is absolute temperature; and c_1 and c_2 are constants relating to temperature and granular features of fresh concrete.

3.2. Model of deformation resistance under vibration

It is well known that vibration can increase the flowability of fresh concrete. That is to say, it can result in a decrease in the deformation resistance. However, few researches on rheological models have treated this phenomenon. Teranishi et al. [15] investigated theoretically the mean deformation resistance of fresh concrete under vibration by simplifying the vibration as a repeated static shear stress and using the Bingham model to express the deformation behaviors of fresh concrete under static stress. As a result, when the vibration acceleration is greater than a certain value, the shear rate — shear stress relationship in the lower shear rate range becomes a curve without a yield value, rather than a straight line as in the Bingham model, as shown in Fig. 4. The flow curve equations in any shear rate range are as follows:

$$\tau = \eta\,\dot{\gamma} \pm \tau_y \quad \text{when}\,|\dot{\gamma}| > \dot{\gamma}_v$$
$$\tau = \eta\,\dot{\gamma} \pm \tau_y\left(1 + \left|\frac{\dot{\gamma}}{\dot{\gamma}_v}\right|\arccos\left|\frac{\dot{\gamma}}{\dot{\gamma}_v}\right| - \sqrt{1-\left(\frac{\dot{\gamma}}{\dot{\gamma}_v}\right)^2}\right) \quad (6)$$
$$\text{when}\,|\dot{\gamma}| \leq \dot{\gamma}_v$$

where $\dot{\gamma}_v$ is shear rate caused by vibration force.

Teranishi et al. further verified the validity of the above model by the dragging ball test of fresh mortar. The advantage of this model is that the flow simulation under vibrated state can be carried out, using the measured values of the rheological constants under static stress. However, the effects of segregation caused by the vibration are not considered, and it is not necessarily applicable to any concrete because it is based on the Bingham model. It is necessary to model the flow behaviors of fresh concrete under vibrated state from the viewpoint of discontinuous body and by using multipoint oscillation theory.

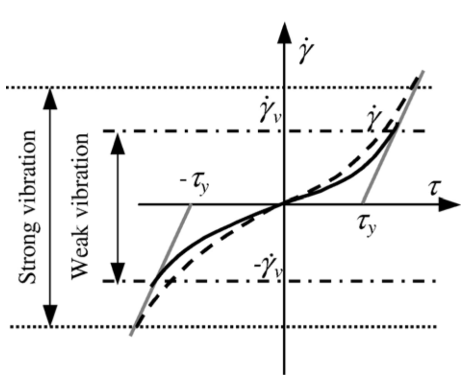

Fig. 4. Consistency curve of fresh concrete under vibration.

3.3. Model concerning segregation resistance

The segregation of fresh concrete generally includes water bleeding and separation of aggregate particles. The segregation decreases the abilities of fresh concrete to pass smoothly through narrow openings between steel bars, and to fill certainly in mould. Moreover, the decrease in the uniformity of fresh concrete may increase its deformation resistance. Thus, in the flow analysis, the uniformity of concrete should be checked frequently and the input data of the rheological constants should be instantaneously modified while the deformation calculation advances. However, There is no the deformation resistance model to consider the segregation's effects, which occurs while fresh concrete deforms or flows, on the deformation resistance now. Predicting the segregation degree and quantifying the variations of the deformation resistance with segregation are two important problems awaiting solution.

Watanabe et al. [61] proposed a constitutive law for quantifying the adhesion between aggregate particles and matrix mortar or cement paste, as shown in Eq. (7).

$$\sigma_{sg} = \sigma_{ad} = \eta_{ad}\,\dot{\gamma}_s \quad (7)$$

where σ_{sg} is adhesive resistance stress; σ_{ad} is adhesive yield value; η_{ad} is adhesive viscosity; and $\dot{\gamma}_s$=segregation rate.

Wang [53] proposed a model for describing the outflow segregation resistance of matrix mortar from fresh concrete, based on the Ruth filtration theory, as shown in Eq. (8).

$$\sigma_g = \sigma_{gy} + \eta_g\,\dot{\varepsilon}_p \quad (8)$$

where σ_g is outflow segregation stress; $\dot{\varepsilon}_p$ is outflow segregation strain rate; σ_{gy} is outflow segregation yield value; and η_g is outflow segregation viscosity.

If the constants in Eq. (7) or Eq. (8) are measured, we can evaluate the segregation resistibility of fresh concrete. The test methods of these constants are also proposed as stated in Section 4. In order to predict the segregation of aggregate particles using Eq. (7) or Eq. (8), the segregation stress between aggregate particle and matrix mortar or cement paste must also be clear. However, the analysis method of the segregation stress has not yet been reported.

3.4. Model of boundary characters

Rheological models describing the restraints on boundary surface of fresh concrete, such as slipping resistance and adhesion resistance, are also indispensable for the flow analysis [22]. However, there is no generally accepted understanding about the behaviors of slipping and adhesion on the boundary, and few research results have been reported.

Table 4
Rheological model of deformation behaviors and direct test methods of rheological constants of fresh concrete

Rheological model	Rheological constants (number)	Measuring methods	Facility	Applicable concrete
(a) Mohr–Coulomb model (Yield condition)	Inter-frictional angle, Adhesive force (2)	Three axes compression test	×	Dry type
		One-side shear test	△	Dry type
(b) Bingham model	Yield value, Plastic viscosity (2)	Rotational rheometers	×	Flowable type
		Dragging-ball viscometer	△	Flowable type
		Parallel plate viscometer	△	Dry type
		Inclined pipe test	○	Flowable type
(c) Combined model (combining (a) and (b))	Varying yield value Varying plastic viscosity (4)	Shear box test	△	Option

[Notes] ×: Very inconvenient, △: Inconvenient, ○: Convenient.

3.4.1. Slipping resistance model

It is known that pressure loss, caused by pumping fresh concrete, more depends on the resistance from the pump pipe's inside surface than the deformation resistance of fresh concrete itself [7]. Tanigawa et al. [50] confirmed experimentally that the slipping resistance depends on slipping rate and vertical pressure acting on the slipping plane, and proposed a linear slipping resistance model for fresh concrete, as shown in Eq. (9). However, since the slipping resistance at such a high slipping rate as in actual pump pipe is not measured, applicable slipping rate range of this linear model is not clear.

$$\tau_s = (S_1\sigma_n + S_2)v_s + (S_3\sigma_n + S_4) \quad (9)$$

where τ_s is slipping resistance stress; v_s is slipping rate; and S_1, S_2, S_3, S_4 are constants.

Though there is some doubt about this model, so far only this simple model has been used actually in the flow analyses in Japan, there have been no reports on other more complex models. Furthermore, the effects of the vibration and the finishing coat of boundary surface on the slipping resistance have not been discussed experimentally or analytically. The lack of study on the slipping resistance on the boundary surfaces, e.g. pump pipe or mould's inside surface, is an obstacle to the development of flow analysis technology.

3.4.2. Adhesive resistance model

At present, investigations on the adhesive behaviors of fresh concrete on its boundary surface have been concentrated on the measurement of adhesive strength. There have been no research reports on the adhesive behaviors from a rheological viewpoint, and no rheological model has been proposed. Hence, it is usual to treat the boundary adhesion as zero tension resistance in the flow analysis. It is considered that the boundary surface is rarely subjected to tension fore, and the deformation on the adhesive boundary plane until the adhesion turns out failure is very small. Thus, the adhesion has relatively smaller effect on the deformation behaviors of fresh concrete.

4. Rheological test methods

4.1. Rheological constants for deformation behaviors

For predicting the workability of concrete by the flow analysis, quantification of the rheological properties of fresh concrete is of course necessary. Table 4 shows the rheological constants associated with the deformation behaviors and their direct test methods. The constants inter-frictional angle and adhesive force term of the Mohr–Coulomb model are usually measured by one-side shear test or three-axis compression test [38,54]. The constants of the Bingham model yield value and

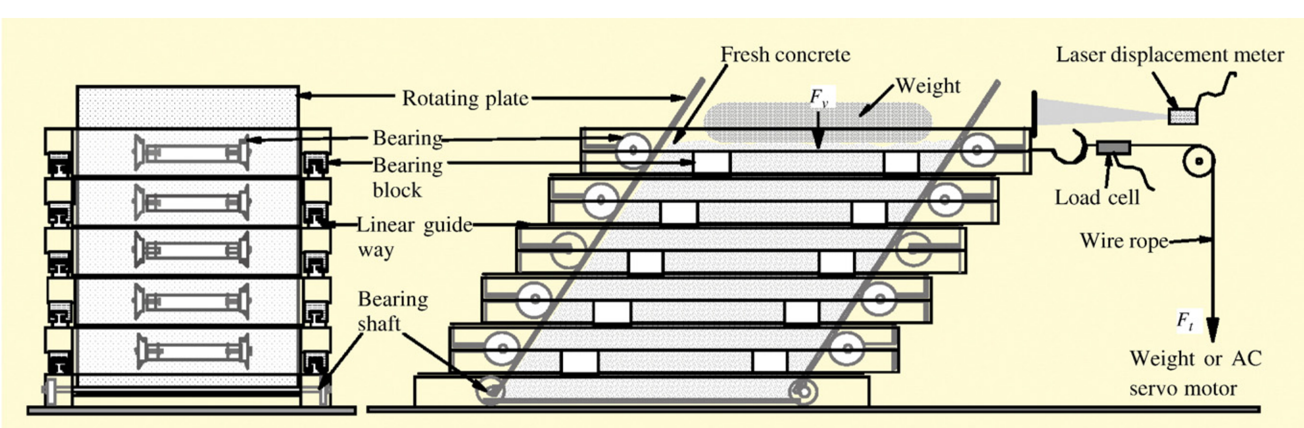

Fig. 5. An example of shear box test apparatus.

Table 5
Methods for estimating rheological constants of fresh concrete

Abbreviated name of method	Combined test results of consistency tests	Facility	Accuracy	Applicable sample
Sl. & Cf.	Slump value and concrete's flow value	△	○	Dry concrete
Sl. & Mf.	Slump value and mortar's flow value	○	⊙	Dry mortar
Mf.	Mortar's flow value	⊙	△	Dry mortar
Sl. & Lv.	Slump value and L-flow velocity	○	⊙	Flowable concrete
Sl. & mLf.	Slump value and mini L-flow velocity	○	⊙	Flowable concrete
Ls. & Lv	L-slump value and L-flow velocity	⊙	△	Flowable concrete
MLs & mLv	Mini L-slump value and mini L-flow velocity	⊙	△	Flowable concrete

[Notes] △: Inconvenient or inaccurate, ○: Convenient or accurate, ⊙: Very convenient or very accurate.

plastic viscosity are usually measured by the Two-point test [62]. The parameters of the combined model considering the effects of vertical pressure should be estimated by a four-point test [2].

The problems of the direct rheological tests except the shear box test have been pointed out by a series of flow analyses [21,37]. Comparisons between five kinds of rotational rheometers — BML, BTRHEOM, CEMAGREF-ING, IBB, and Two-point rheometer have also been reported [40]. Any of these rheometers is not widely applicable to any concrete, generally is used for the rheological evaluation of concrete having flowability. Also, the slip at the interfaces between concrete and rheometer's container wall, or/and the confinement of concrete between moving parts of the rheometers are other big problems of the rotational rheometers. In recent years, the L-flow test [41] has been widely used to measure the flow rate that is related to the viscosity of fresh concrete. However, like other rheometers, its application is still limited to flowable concrete.

The stratified shear box test [42,43] may be widely applied to various kinds of concretes including dry concrete, and to the measurement of other rheological constants besides the Bingham constants. An example of the stratified shear box apparatus of horizontal type is shown in Fig. 5 [43]. Though the slipping resistance between box inside and concrete specimen is

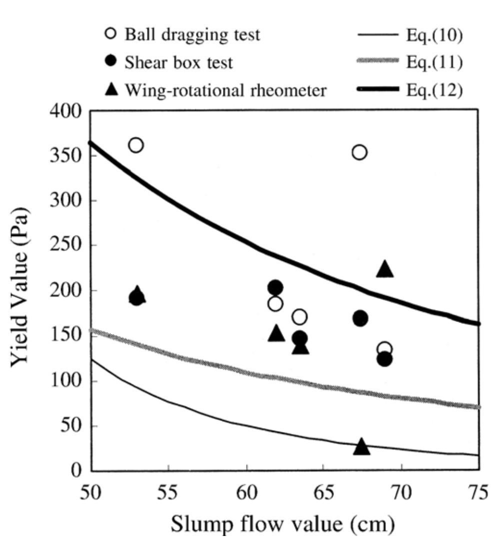

Fig. 6. Comparison between the estimating results from the slump flow value and the actual measuring ones for the yield value.

greatly decreased by stratifying the box, how to completely remove the effects of the slipping resistance from the test results is a great problem. Moreover, the stress state, caused by shear fore and concrete's weight, and its effects on the test results are not clear.

Facing the difficulties in the direct measurement of the Bingham constants, it is necessary and significant to estimate them from consistency tests. Available estimating methods are shown in Table 5 [30,45,46]. However, up till now, there have been no usually accepted estimating method for all kinds of concretes, and the difficulty in newly developing a handy and widely applicable test method has been generally recognized. The estimating equations based on the slump flow test or L-flow test, are respectively proposed, as shown in Eq. (10) [77], Eq. (11) [78], Eqs. (12) and (13) [70], and Eq. (14) [79]. When calculating the plastic viscosity by using Eq. (14), the yield value is necessary, which can be estimated by any of Eqs. (10)–(13).

$$\tau_y = \frac{15^2 \rho G V^2}{4\pi^2 \mathrm{Sf}^5} \tag{10}$$

$$\tau_y = \frac{\rho G V^2}{\pi \mathrm{Sf}^2} \tag{11}$$

$$\tau_y = \frac{4\rho G V}{\sqrt{3}\pi \mathrm{Sf}^2} \tag{12}$$

$$\eta_{pl} = 125.3\left(1 - \frac{4\times10^4}{\mathrm{Sf}^2}\right)\left(1 - \frac{25\times10^4}{\mathrm{Sf}^2}\right)t_{500} \tag{13}$$

$$\begin{aligned} \eta_{pl} &= \left(\frac{L_{t5-10}}{b\tau_y^2 + c}\right) \\ b &= 8.3\times10^{-11}/\rho - 2.4\times10^{-8} \\ c &= 3.8\times10^{-6}/\rho - 5.0\times10^{-5} \end{aligned} \tag{14}$$

where τ_y is yield value (Pa), η_{pl} is plastic viscosity (Pa · s), Sf is slump flow value (mm), L_{t5-10} is the elapsed time when the flow distance in L-flow test increases from 5 cm to 10 cm (s), t_{500} is the elapsed time when the slump flow in the slump test reaches 500 mm, ρ is the density of concrete (g/mm^3), G is gravity acceleration (mm/s^2), V is volume of specimen (mm^3).

Comparisons between the estimating results and the actual measuring results of the Bingham constants are shown in

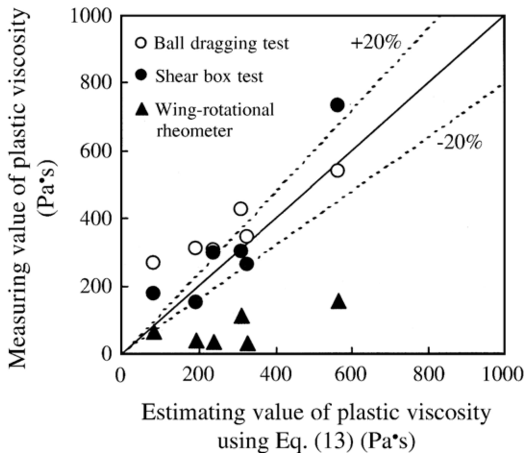

Fig. 7. Comparison between the estimating results by Eq. (13) and the actual measuring ones for the plastic viscosity.

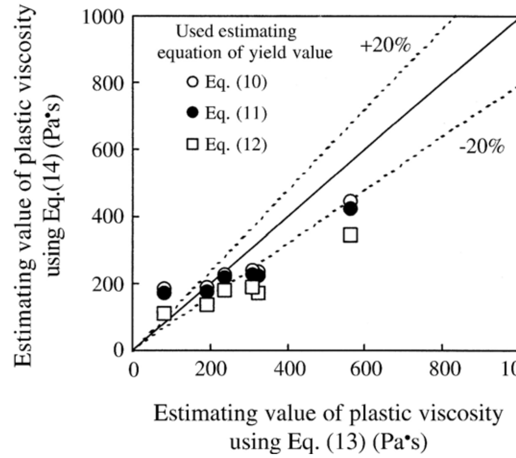

Fig. 8. Comparison between the estimating results by Eq. (13) and those by Eq. (14) for the plastic viscosity.

Figs. 6–8 [80]. As shown in Fig. 6, the estimating result of yield value from the slump flow values is greatly dependent on the used equation, this dependence is caused by the difference in the yield conditions used for inducing the estimating equations. Also, Many measuring values are between the estimating values by Eq. (11) and those by Eq. (12). Fig. 7 indicates the relationship between the estimating values of plastic viscosity by the Eq. (13) and the measuring values using three kinds of apparatuses. The estimating values of plastic viscosity are close to the measuring values by the dragging ball test and the shear box test, but deviate from the measuring values by the wing-rotational rheometer. Also, the estimating values from the Eq. (14), in which the yield value is estimated by the Eq. (10) or (11) or (12), are smaller than those from the Eq. (13), as shown in Fig. 8.

Another matter of grave concern is that the reported test methods cannot yield consistent values of rheological properties even for the same concrete mix. It is considered that this problem is caused by the differences between the test methods in the assumptions for calculating the rheological constants, and in the degree of slip at the concrete/wall interface [40], as well as in the test conditions, including stress duration, normal stress on shear plane, stress history, loading rate, level and range of shear rates used in the measurement, specimen size, etc. [48,49,55]. Chiara introduced relative Bingham constant (whole concrete to matrix mortar) in an attempt to compare the test results from different rheometers [47].

Using the Bingham constants to characterize the deformation behaviors of non-high-fluidity concrete is not appropriate. Thus, there is some doubt about the meaning of measuring the Bingham constants for ordinary concrete. New rheological constants and applicable test methods are needed to propose for ordinary concrete

There have been several reports on the measurement of the Bingham constants of fresh concrete subjected to vibration, using the vertical pipe test [63] or the dragging ball test [15,64]. However, there is some doubt about the validity of these test results because the vibration acceleration is not the same everywhere in the specimens of fresh concrete.

4.2. Rheological constants concerning segregation resistance and boundary characteristics

Wang [53] proposed an outflow segregation resistance model for matrix mortar, as stated above, and measured the constants of this model — yield stress and viscosity of outflow segregation of matrix mortar, using a filtering test (Fig. 9). However, the meaning of the measuring result of the outflow segregation resistance at the initial stage of matrix mortar outflow is not clear, and this test method is hard to apply to low fluidity concrete.

Up to now, few test methods have been proposed for the constants of the slipping resistance model and the adhesion strength. Fig. 10 shows an apparatus for slipping resistance test [50]. The adhesive force between specimen and boundary surface is measured mostly by one-axis tension test. Fig. 11 shows a representative test device for adhesion strength [51].

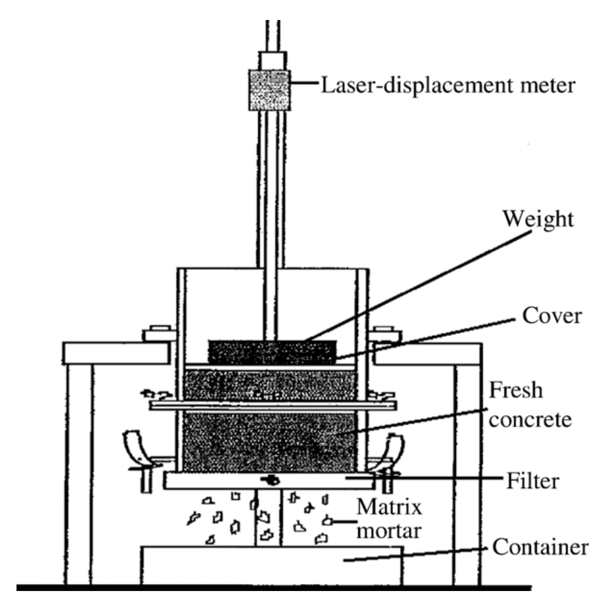

Fig. 9. Outflow segregation test device of matrix mortar.

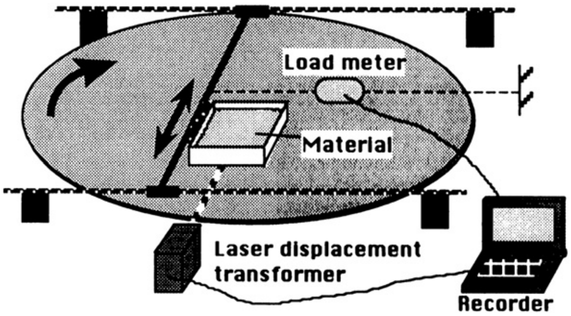

Fig. 10. Slipping resistance test.

However, test results of the rheological constants of the slipping resistance model and the adhesive strength vary greatly with material used and state of boundary surface. Thus, it is difficult to develop a test device for comprehensively treating all test conditions. Furthermore, the measurement at a higher slipping rate has not yet been realized. Although the adhesion strength is measured by one-axis tension test, the specimen at the boundary could be in a multiple stress state when the adhesion falls in failure, so the calculation of adhesion strength is not reliable [52].

5. Flow analysis methods

Few numerical flow analysis methods have been proposed for fresh concrete. The main numerical methods reported and their characteristics are shown in Fig. 12. They can be classified into two types according to the analytical models used — continuous body model and discontinuous body model.

5.1. Flow analysis methods based on continuous body model

It can be said that it is a very bold assumption to consider fresh concrete as a continuous body. This assumption facilitates the calculation procedure, but the evaluation and modeling of material properties becomes complicated, and the boundary conditions are difficult to set up in large deformation analysis.

5.1.1. Visco-plastic finite element method

To establish a general flow analysis technology for fresh concrete, visco-plastic finite element method (VFEM) using the Bingham model was first proposed [65]. As its initial calculation method, static balance equation of applied forces

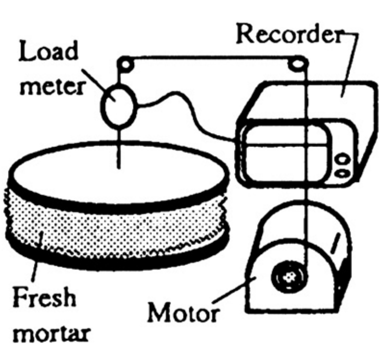

Fig. 11. Adhesion strength test.

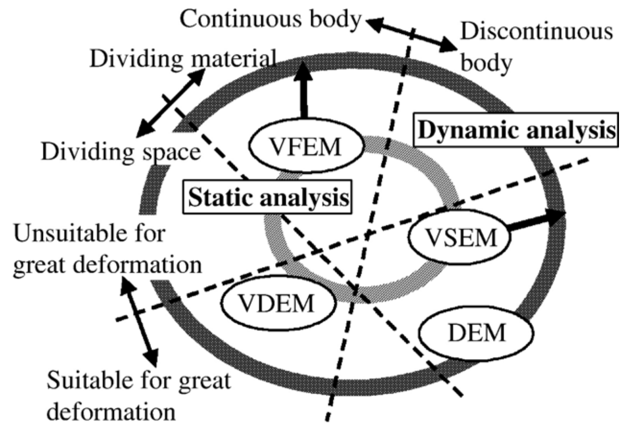

Fig. 12. Numerical flow analysis methods for fresh concrete.

was used, and the influences of inertia force were approximately treated. However, for handling the problems of rapid deformation or flow, dynamic calculation, based on the motion equations, has recently become the mainstream [28]. This dynamic VFEM can treat the volume elasticity of liquid to make it possible for the first time to reproduce numerically the propagation phenomenon of vibration [30]. There are a lot of examples of flow analysis using the VFEM, and most of the flow analyses on the consistency tests shown in Table 2 have used this numerical method. The validity of the VFEM has been also confirmed by the studies shown in the Refs. [22] and [23].

However, it is pointed out that if we use a rheological model more accurate than the Bingham model in the dynamic VFEM, the precision of flow analysis can be improved [32]. The VFEM is possibly applicable to three-dimensional problems, but it is difficult to be used for practicable problems such as simulation of casting fresh concrete in mould with cross-placed steel bars, because of the complexity of boundary conditions and the limitations of the freedom of the nodes.

5.1.2. Pulsation analysis of pumping

Pulsation of pumping pressure was successfully analyzed by one-dimensional calculation using the dynamic VFEM [9]. Input parameters for the calculation are viscosity and yield stress of deformation and slipping, as well as volume elasticity, respectively characterizing the dashpot, slider and spring shown in Fig. 13. Complex and large-scale pumping experiments for confirming concrete's pumpability and pressure loss may be possible to replace by this numerical analysis in the future. The present problem is how to quantify the material properties that

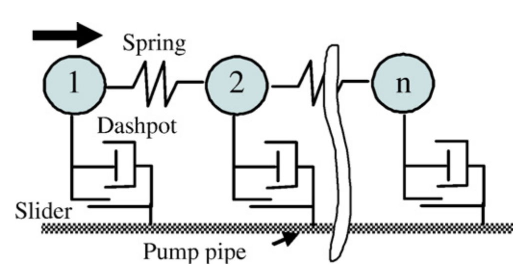

Fig. 13. One-dimensional analysis model of pumping.

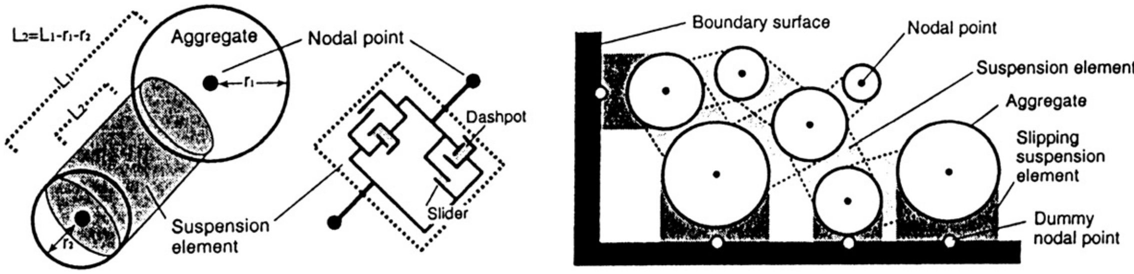

Fig. 14. Nodes (aggregate) and elements (matrix mortar or cement paste) of suspension element method.

are the input data used in this analysis. Pumpability, which is greatly influenced by the flow behaviors of fresh concrete in the state of high-rate flow, is an extremely important factor that should be considered in mix design of concrete. It is experimentally confirmed that the pulsation of pumping pressure cannot be explained by a stable flow analysis using the flow theory of capillary tube. Thus, dynamic calculation as the analysis stated above will likely become the main current in the future.

5.1.3. Visco-plastic divided space element method

In the analysis process of the visco-plastic divided space element method (VDEM) [65], the space, in which fresh concrete is cast, rather than the fresh concrete, is divided into many elements, and the characters of individual element vary with the inflow of fresh concrete. The strain rate at each node is obtained by a repeated calculation with time steps, and the movement of an imaginary ball cock called a marker images the flow of fresh concrete during casting.

Although this numerical method is based on a continuous body model, it can reproduce the phenomena of large deformation, break-up, massing, collision, etc. of fresh concrete. Concrete's casting simulation in a practical scale becomes possible by using the VDEM, though a large calculation capacity is needed for computer. Moreover, because the VDEM is the most suitable for making concrete flow visible, its application to the visibility field of concrete flow can be expected in the future [19].

However, the VDEM can't be used in three-dimensional analysis now. Furthermore, the filling situation of fresh concrete in a mould is relatively easily clarified in outline by using this numerical analysis method, but the flow in small-scale spaces such as mould's corners, and the finishing state of fresh concrete are hard to simulate.

5.1.4. Theoretical analysis methods

There have been a lot of reports on the theoretical analysis of concrete flow in pipe, including common analyses [7,66], complete analyses considering deformation and slipping [5,67], and special analyses treating the flow in various shaped pipes such as tapered pipe [6,7]. However, the present guideline for pumping construction, established by the Architectural Institute of Japan, is only based on the experimental relation between pressure loss and slump value [68]. The pipe flow theory has not been applied to actual design of pumping construction.

The pipe flow theory has been employed in the flow analyses of the inclined tube test [31] and the funnel test [27] of concrete. Furthermore, using the logic of this theory, the behaviors of fresh concrete, flowing through reinforced steel bars, have been successfully analyzed [10,69].

Another theoretical analysis, called slumping theory, has been reported to clarify the deformation behaviors of fresh concrete during slump test [23,69]. This method makes it possible to show the behaviors of fresh concrete in the process of slumping, which can't be explained by previous theoretical results [20] and experimental ones of the relationship between the yield stress and the slump value. Moreover, it was successfully used to develop a method for estimating the plastic viscosity of high fluidity concrete from the test results of slump flow velocity [69]. It is expected to clarify flow phenomena in more wide-range for fresh concrete by a combined theoretical analysis of pipe flow theory and slumping theory in the future.

5.2. Analytical methods based on discontinuous body model

Many phenomena during fresh concrete flows, e.g. passing through reinforced steel bars, segregation, and blockage, are associated with concrete workability. These phenomena are caused by non-homogeneity of concrete. Analytical techniques based on the multi-phase model shown in Table 3, are naturally required for precisely reproducing the flow behaviors of fresh concrete. However, several analytical methods using two-phase model of coarse aggregate and matrix mortar have been only proposed now [4,71].

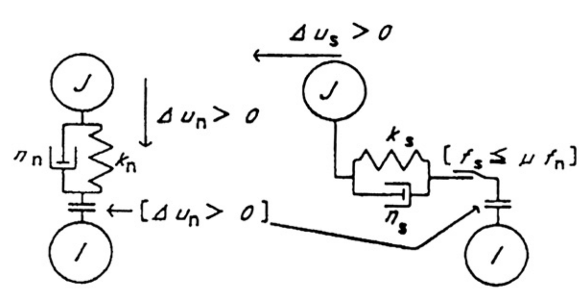

Fig. 15. Analysis model of distinct element method.

5.2.1. Visco-plastic suspension element method

Visco-plastic suspension element method (VSEM) is the first numerical analysis method using a discontinuous body model for the flow analysis of concrete [72]. It adopts the two-phase model, and is based on the extremely bold simplification that fresh concrete is a three-dimensional truss structure with node points of spherical coarse aggregate, as shown in Fig. 14. It is possible to improve the precision of the VSEM by using a more complex element model than the current truss structure model, but the analytical results even using the current truss model can relatively well reproduce the actual flow behaviors of fresh concrete. The accuracy necessary for the flow analysis of fresh concrete needs to be fully discussed.

Dynamic calculation has already been introduced in the VSEM [17]. The calculation process of dynamic VSEM is similar to that of the distinct element method (DEM) described later. However, the dynamic VSEM and the DEM have opposite concepts of node and element, and the visco-deformation elements in the dynamic VSEM have each dimension. Moreover, the DEM is mainly used to predict the failure or yield behavior of fresh concrete, whereas the principal object of the VSEM is to simulate the flow behaviors after yielding.

The VSEM can be applied to three-dimensional flow analysis, and due to the simplicity of boundary conditions, it has already been used to simulate many flow phenomena of fresh concrete [4,8,17]. However, because it needs a huge calculation capacity for computer, the VSEM is now only used for the flow analyses in relatively small-scale spaces.

5.2.2. Distinct element method

The distinct element method has recently been introduced into the flow analysis of fresh concrete as a numerical method using discontinuous body model [73,74]. This method is based on a motion equation of rigid elements and the transmission of forces between the rigid elements. When the DEM is applied to the flow analysis, dashpots and springs must be first set up between the rigid elements (Actually they are particles in fresh concrete) to express viscous resistance and inter-frictional resistance of concrete, as shown in Fig. 15. However, the dashpot and the spring have no dimension, and there is the big problem that the used input data are imaginary values, which are not directly related to the measured rheological constants — yield value and plastic viscosity of matrix mortar at present.

5.3. Theoretical analysis methods

Examples of theoretical analyses using discontinuous body model have been reported on the moving behaviors of coarse aggregate particles in vertical pipe, tapered pipe, and divergent pipe when fresh concrete is pumped [44,71,75,76], and the segregation of coarse aggregate from matrix mortar when fresh concrete passes through reinforcing bars [10]. Although these theoretical analyses are only qualitative examinations of actual phenomena, this kind of theoretical investigation on the motion of coarse aggregate particles is expected to promote the discussion how to define the segregation and blockage behaviors of fresh concrete.

6. Conclusions

The way and the element technologies necessary for establishing the workability design method of concrete has been recognized in Japan. However, most studies are in the first stage now, which is how to quantitatively estimate the rheological properties. Development of the rheological test methods, which can be easily conducted by anybody at any time and place, is still an important problem. Rheological test methods of fresh concrete are also needed to standardize internationally. The backup of theoretical or/and numerical analysis is effective for designing suitable rheological test apparatuses.

The quantitative measurement of the rheological properties of fresh concrete is indispensable, but it may be more important to look ahead to the purposes of measuring material's rheological properties. We must always ask ourselves how we use the results of rheological tests, and what data or indexes we should measure.

It can be said that there has been too little effort to establish the prediction technology of concrete's workability. The problems awaiting solution in this field are summarized as follows:

The first is to determine a constitutive law for fresh concrete, which gives great effects on the development or selection of rheological test methods and suitable theoretical and numerical analysis methods. To construct an appropriate constitutive law applicable to any kind of fresh concrete, an investigation from the standpoint of discontinuous body rather than homogeneous viscous fluid is necessary.

The second is to model various construction and structural conditions. It is necessary to investigate how to model and express numerically the effects of reinforcing bars' size and density, vibration, etc.

The third is to develop reasonable numerical flow analysis method applicable to any kind of fresh concrete.

These problems are interconnected with each other, so an attention should always be given to the overall situation when studying these problems. Of course, they can not be solved only by separate efforts of a few researches. International cooperative research in the long run is necessary and effective.

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