Application of "The Water Layer Model" to self-compacting mortar with different size distributions of fine aggregate

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Self-Compacting Concrete is a relatively new type of concrete. Up to now only a few models have been developed to explain its physical behaviour, like the Water Layer Model and the Excess Paste Model. In this paper, the difference between the Water Layer Model and the Excess Paste Model is discussed and the validity of the Water Layer Model to Self-Compacting Mortar with different characteristics of the sand is investigated. The results of this investigation show that the Water Layer Model is effective for the determination of the quantity of water. Furthermore the function of water and superplasticizer is explained using this model.

Key words: Self-compacting concrete, water layer model, sand size distribution

1 Introduction

The necessity to use self-compacting concrete was advocated by Prof. Okamura in 1986 [1]. His arguments have been accepted not only in Japan but as well in other countries all over the world. Research on self-compacting concrete has been intensely carried out in various research institutes for more than 15 years. Especially, the mix design methods were investigated, considering the different conditions in various countries. This was necessary be-

cause the properties of self-compacting concrete in the fresh state are substantially different from those of conventional concrete. However, most investigations focused on finding the necessary content of water and superplasticizer.
The workability of a fluid is traditionally characterized by a viscometer test, by which the rheologic properties of the mixture are characterized according to the Bingham model. Using this relation the workability is characterized by the parameters yield value and plastic viscosity. However, viscometer tests are hard to perform under in-situ conditions. Therefore, as an alternative, in Japan a combination of two simple tests is used: the flow cone and the so called V-funnel test, see Figure 1. The slump flow test gives an indication of the yield value of the concrete. The time that a fixed volume of concrete needs to pass the V-funnel is an indication for the plastic viscosity. According to the Japanese mix design method for prototype SCC, the content of water is chosen in such a way that it leads to a slump flow diameter of 650-700 mm. The type and content of superplasticizer are chosen in order to achieve a funnel passing time of about 10 seconds. In Japan meanwhile significant experience has been gained with this method [2]. However, making self-compacting concrete still is a trial and error procedure and requires a lot of time because the fresh concrete properties depend largely on the type of solid material, the mixture ratio of the solid materials and the mixing method.

In order to improve this, the first author has proposed the Water Layer Model [3, 4] to determine the quantity of water that is necessary for self-compacting concrete. This model assumes that "if the fresh properties of self-compacting concrete are the same, the thickness of the water layer retained by the surfaces of the powder particles is also the same". "Powder" is defined as the collection of particles (cement and fillers) with a diameter smaller than 0.09 mm. Then the quantity of water for self-compacting concrete can be calculated from the size distribution of the powder used. However, because the volume

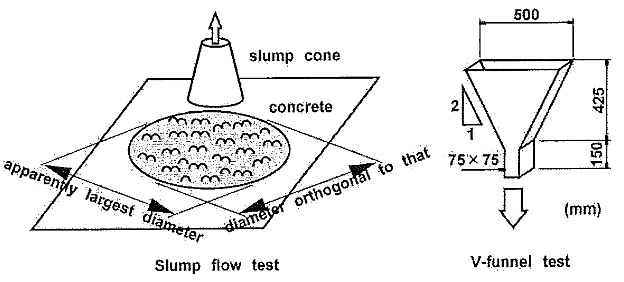

Figure 1: Flow cane and funnel test to characterize the workability of self-compacting concrete

fraction of the fine aggregate (normal river sand particles with diameters 0.09 – 4 mm) in the mortar was fixed at 40% and the amount of coarse aggregate (with diameters 4 – 16 mm) was fixed at 50% of its solid volume respectively in this study, this model cannot be applied when the aggregate content changes. This aspect requires further investigation. This experimental study deals with the variation of size distribution and volume content of the fine aggregate in self-compacting mortar to expand the applications of the water layer model. This research program is subdivided into the following steps.

1. Investigation of the thickness of the excess paste layer in self-compacting mortar.
2. Investigation of the thickness of the excess water layer in self-compacting mortar.
3. Application and confirmation of the Water Layer Model for self-compacting mortar.

2 Characteristics of the applied materials

2.1 Cement

Blast furnace slag cement CEM Ill/B 42,5 LH HS at a density of 2.96 g/cm^3 and a Blame value of 401 m^2/kg was used for these experiments. This is commonly used cement in the Netherlands. It is rare to use only Portland cement for making self-compacting concrete, because reactive powders cause some problems with regard to autogenous shrinkage and heat of hydration. Limestone powder, fly ash, and blast furnace slag are usually applied in combination with Portland cement, and a low heat Portland cement is sometimes applied as a single powder.
Figure 2 shows the particle size distribution of the applied cement. It was measured by a laser diffraction instrument. It is important to note that the size distribution of a powder

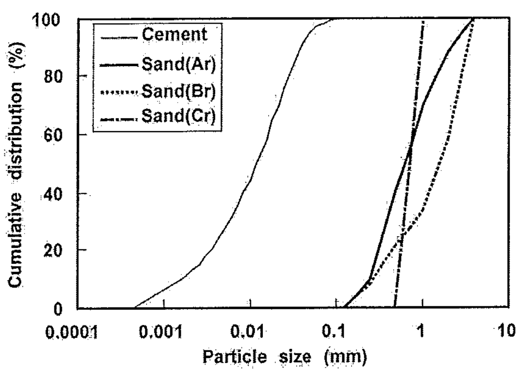

Figure 2: Size distribution of solid materials used in the tests measured by laser diffraction

Table 1. Characteristics of the fine aggregates used in the experiments

Type	Ar River sand	Br River sand	Cr River sand
Specific gravity*	2.60	2.59	2.61
Absorption (%)	0.59	0.91	0.54
F.M.	2.93	3.79	3.00
Solid volume (%)	68.2	71.6	62.7
0.125 ~ 0.25mm	9.3	8.3	0
0.25 ~ 0.5 mm	30.2	12.5	0
0.5 ~ 1 mm	30.2	12.5	100.0
1 ~ 2 mm	18.6	25.0	0
2 ~ 4 mm	11.6	41.7	0
total (%)	100.0	100.0	100.0

*saturated surface dry base

Table 2. Combination of experiments (s/m = sand to mortar volume)

s/m	0%	10%	20%	35%	40%	45%	50%	55%	60%
Paste	*								
Ar				*	*	*	*	*	
Br		*	*	*	*	*	*	*	*
Cr		*	*	*	*	*	*		

differs if different measuring methods are used. The size distribution is a very important characteristic for calculating the thickness of the water layer.

2.2 *Chemical admixture*

Many kinds of superplasticizers can be applied to make self-compacting concrete. Examples are Aminobenxen sulfonic acid-based, lignin sulfonic acid-based, melamine sulfonic acid-based, naphthalene sulfonic acid-based and polycarboxylic sulfonic acid-based superplasticizer. Nowadays, in many cases polycarboxylic sulfonic acid-based superplasticizer are used at the building site. Therefore, this type of superplasticizer was applied for the experiments. The superplasticizer which was used in the experiments is a polycarboxylic ether complex type superplasticizer with a density of 1.05 g/cm^3. It is a product readily available at the Dutch market. It has a low initial dispersibility, but it has a high ability for slump retention.

2.3 *Fine aggregates*

Table I shows the characteristics of the fine aggregates. The maximum size of the sand is 4 mm. Figure 2 shows the size distribution. The sand had been classified into five groups of grains (0.125 ~ 0.25 mm, 0.25 ~ 0.5 mm, 0.5 ~ 1 mm, 1 ~ 2 mm and 2 ~ 4 mm). Their fractions were blended on beforehand and sand with different size distributions (Ar, Br and Cr) were used for the experiments. The sand Cr is an almost single grain fine aggregate in the range of 0.5 ~ 1 mm. The packing density of the fine aggregates was measured according to JIS A 1104-1999. Table 2 shows the combinations of fine aggregate volume ratios that were used in the experiments. The figures 3-5 show the size distributions of the mixed solid materials for the series Ar, Br and Cr, which are rather different.

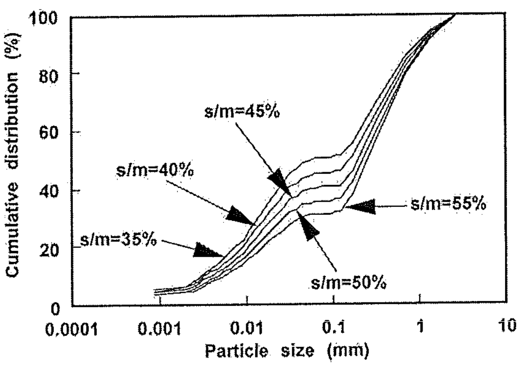

Figure 3: Size distribution of mixed solid materials (Series Ar) for various sand/mortar (s/m)ratios

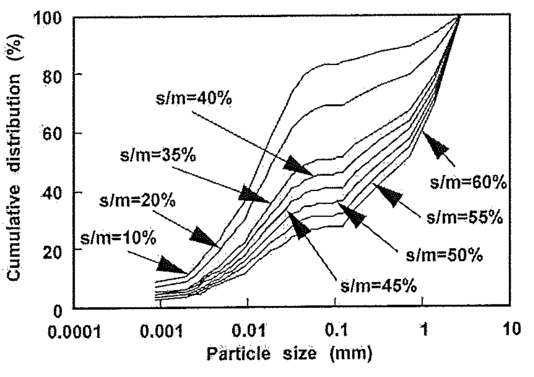

Figure 4: Size distribution of mixed solid materials (Series Br) for various s/m ratios

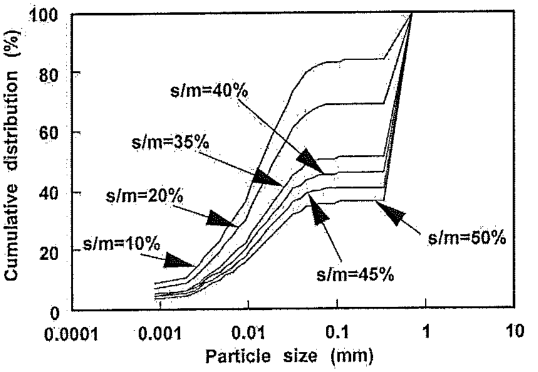

Figure 5: Size distribution of mixed solid materials (Series Cr for various sand/mortar ratios)

3 Experimental program

3.1 Mixing procedure

Mortars, which had the same flow diameter (245 mm) and the same flow time through the V-funnel (10 sec), were made using the materials mentioned before. 3.5 litres of mortar were mixed using a Hobart mixer (capacity of 11 litres, possible revolution of 48 rpm, maximum rotation of 110 rpm). The mixing procedure is shown in Figure 6. The quantity of the first charge of water was fixed at 0.7 times the water retaining ratio β_p (βp = 1.040) according to the Japanese mix design method. E_p (E_p = 0.0506) is the deformation factor of the paste: these values were found using the paste flow test. According to this test the flow diameter of a paste is measured after lifting a fully filled cone with a height of 60 mm, an upper circular opening of 70 mm and a lower circular opening of 100 mm [2]. A resting time of 5 minutes was arranged before finalising the mixing procedure (Fig. 6) because the initial dispersibility of this superplasticizer was weak and the flowability of the mortar could possibly increase after mixing.

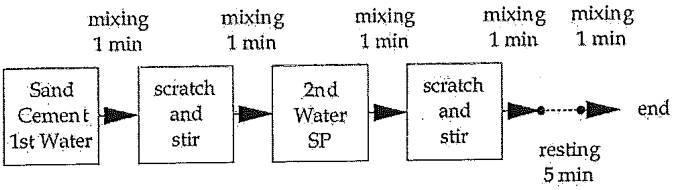

Figure 6: Mixing procedure for mortar

3.2 *Mortar flow test*

After mixing, the flow diameter of the mortar was measured in two directions (the apparently largest diameter and the diameter orthogonal to that). This measurement was carried out twice simultaneously.

The water to powder volume ratio (V_W / V_p) and the superplasticizer content (SP/P) were adjusted until an average flow diameter of the mortar of 245 +/- 10 mm was obtained. Generally, the flow diameter is affected by SF/P.

3.3 *V-funnel test*

After mixing, the flow time through the V-funnel was measured twice. The water to powder volume ratio (V_W / V_p) and the superplasticizer content (SF/F) were adjusted till an average flow time of the mortar of 10 +/- 1 sec was obtained. Generally, the flow time is affected by V_W / V_p.

3.4 *Packing density of the solid materials in mortar*

Once the target mortar was achieved, the packing density of the solid materials (cement and sand) was measured in order to calculate the quantity of retained and free water in the mortar. The retained water is defined as the amount of water that fills the voids between the solid particles. The free water is defined as the amount of water that is not retained by particles; it can move around the particles. The water layer covering the particles consists of this free water.

The mortar (about 27 cm^3) was cast into a plastic container (diameter of 22 mm, height of 90 mm) of a centrifuge. A centrifugal cylinder separation was carried out at 4000 rpm during 10 minutes. After that, the free water which rose up to the surface of the mortar was removed, what means that only retained water remains in this mortar. The packing density of the solid materials was calculated from the weight of the remaining mortar related to that of the mortar, before centrifuging was adapted. This measurement was carried out using eight containers simultaneously. The mean value was applied for further investigation.

3.5 *Filling capacity test*

Once the target mortar was found, a filling capacity test [5] mortar was carried out on the mortar. The test device, measuring the filling capacity, is shown in Figure 7. The pipe (inner diameter of 25 mm) was fixed 15 mm above the base in the middle of a transparent plastic container (diameter of 152 mm). The circumferential area was randomly filled with 412 spherical ceramic balls (diameter of 24 mm). 3 Litres of mortar, which were poured in the upper funnel, flows through the pipe after opening an outlet gap, and fills the transparent plastic container. The filling height was measured as soon as the flow stopped. The measured height was then defined as the filling capacity. The filling capacity is affected by the diameter of the ceramic balls. During the experiments the same diameter and number of balls was used. The mortar is qualified as having a good filling capacity if the filling height is larger than 250 mm.

4 Results and discussion

4.1 *Overview of the test results*

Table 3 shows the mixture proportions and the properties of the target mortars for the adapted 20 combinations. It should be noted that s/m is the ration sand to mortar in volume %, Sp/P is the percentage of superplasticizer to powder in mass and the packing density it the percentage of solid volume to total volume of the aggregate. It was possible to achieve target mortars until a sand content (s/m) of 55% for Ar, a s/m of 60% for Br and a s/m of 50 % for Cr, respectively. The flow diameter has to fulfil the target range of 245 +/- 10 mm and a V-funnel time of 10 +/- 1 second. The target values were achieved for all mortars, except for those with an s/m of 55% for Ar and an s/m of 55% for Br. However,

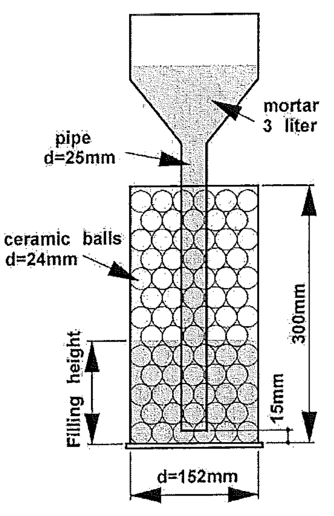

Figure 7: Dimensions and principle of the apparatus for compatibility test

Table 3. Results of mix proportion and properties of mortar

Type of sand	s/m (%)	V_w/V_p	SP/P (%)	Unit weight (kg/m³)			Flow (mm)	V-funnel (sec)	Filling height (mm)	Packing density (%)
				water	cement	sand				
Paste	0	0.780	0.750	438,2	1662,9	-	238	9.6	291	58.4
Ar	35	0.810	0.870	290,9	1063,0	910,7	249	9.1	289	72.5
	40	0.820	0.880	270.3	975.8	1040.8	241	9.4	285	74.4
	45	0.840	0.910	251.1	884.8	1170.9	240	9.7	148	76.3
	50	0.890	0.950	235.5	783.1	1301.0	249	9.4	11	78.0
	55	0.960	1.100	235.7	634.3	1431.1	238	11.1	0	79.6
Br	10	0.780	0.770	394.4	1496.6	259.0	239	9.8	267	62.3
	20	0.785	0.800	351.8	1326.6	518.0	250	9.6	147	66.3
	35	0.800	0.860	288.9	1068.9	906.5	250	9.4	47	72.5
	40	0.800	0.850	266.7	986.7	1036.0	242	10.1	0	74.8
	45	0.820	0.910	247.8	894.5	1165.5	239	10.8	1	76.6
	50	0.850	0,950	229.7	800.0	1295.0	253	10.1	0	78.5
	55	0.880	1.000	210.6	708.5	1424.5	256	10.0	-	80.5
	60	0.970	1.040	197.0	601.0	1554.0	245	10.0	-	82.3
Cr	10	0.779	0.770 -	394.1	1497.5	261.0	237	9.4	285	62,4
	20	0.780	0.800	350.6	1330.3	522.0	251	8.7	300	66.6
	35	0.790 -	0.870	286.9	1074.9	913.5	237	10.2	289	73.0
	40	0.815	0.850	269.4	978.5	1044.0	237	9.5	280	74.8
	45	0.830	0.890	249.5	889.6	1174.5	236	10.1	275	76.8
	50	0.870	1.050	232.6	791.4	1305.0	249	9.3	3	78.7

their deviation from the target values was very small: therefore, the target mix proportion may be almost the same as this result. The measurement of the filling height at an s/m of 55% and an s/m of 60% of the sand Br was not carried out because it was supposed that they would have a filling height of approximately zero.

Figure 8 shows the relationship between the volume fraction of the fine aggregate in the mortar (s/m) and the water to powder volume ratio (V_W/V_p). The relationship between s/m and the superplasticizer content (SP/P) is given in Figure 9. To achieve a mortar having the same properties in the fresh state, (V_W/V_p) and SP/P both should be increased exponentially with an increasing ratio s/m. Moreover, this relationship is affected by the distribution of fine aggregate. A sand having a low fineness modulus (F.M.) needs more water and superplasticizer than the sand with a larger F.M. For the same s/m in mortar, the number of sand particles increases with decreasing F.M. Therefore, the probability of collision and friction between the sand particles increases if F.M. decreases. The increase of collision and friction makes the mortar stiffer. To keep the target values of the mortar, the

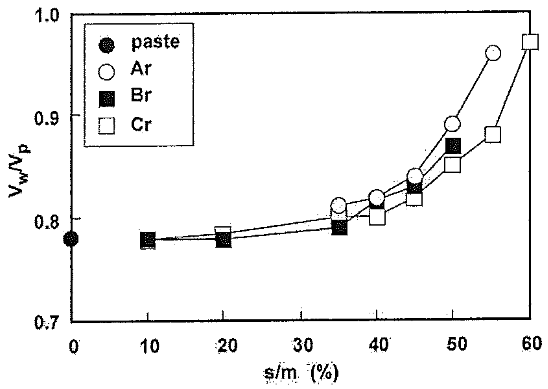

Figure 8: Re1ationslip between fine aggregate volume and water to powder volume ratio

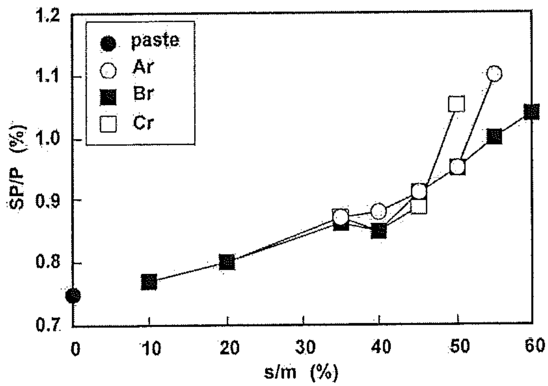

Figure 9: Relationship between fine aggregate volume and superplasticizer content

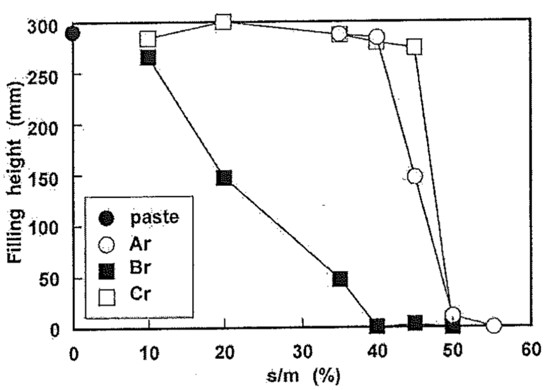

Figure 10: Relationship between fine aggregate volume and filling height

yield value and viscosity of the paste should be decreased in order to allow the sand particles to move easily.

Figure 10 shows the relationship between s/m and the filling height. The filling heights of Ar and Cr are almost the same. The filling capacity falls drastically if s/m surpasses a value of about 40%. According to Ozawa [6], blocking of mortar occurs easily at an s/m of about 44%. This result agrees well with the own experiments. Anyhow, the filling height of Br is always low. The s/m of Br should be decreased below 10% in order to satisfy the designated targets. As mentioned above, the filling height is affected by the diameter of the ceramic balls. If it is assumed that the ceramic balls (diameter of 24 mm) are a regularly arranged simple rhombic system, the diameter of the inscribed circle between the ceramic balls would be 3.713 mm (see Figure 16). The mortar has to pass this inscribed circle in order to fill up the container. Therefore, the ratio of the diameter of the inscribed circle to the diameter of the sand is an important criterion to describe the results of the filling height tests. The median diameters of the sands Ar, Br and Cr are 0.636 mm, 1.587 mm and 0.707 mm respectively (see Figure 2). The ratio between the median sand diameter and the diameter of the inscribed circle between the ceramic balls for the sands Ar, Br and Cr is 0.171, 0.427 and 0.190, respectively. The ratio of Br is the highest of all types of sand. Figure 2 shows that the size of a large percentage of the sand particles of Br is larger than the circular opening diameter. This explains that filling the container with sand Br is much more difficult than for the other sands.

4.2 Investigation of the thickness of the excess paste layer in self-compacting mortar

The "Excess Paste Theory" was proposed by Kennedy nearly 70 years ago [7]. Figure 11 shows an outline of this theory. A concrete sample with space between the aggregates is shown in Figure 11 (a). The aggregates are covered by cement paste. One could compact the aggregates, and squeeze out the excess cement paste surrounding them as shown in Figure 11 (b). The cement paste can then be separated into two parts: the top layer which is formed by the excess paste and the bottom layer which is the cement paste that fills the voids between the aggregates. These cement paste parts are denoted as 'excess paste' and 'compact paste', respectively. The volume of the excess paste (V_{ep}) is calculated by subtracting V_{cp}, the volume of compact paste, from V_{p}, the total volume of paste, as shown in Equation 1.

$$V_{\text{ep}} = V_{\text{p}} \pm V_{\text{cp}} \tag{1}$$

Here, it is important to indicate the differences between the Excess Paste Theory and the Water (Paste) Layer Model. In order to calculate the thickness of the excess paste, the total surface area of the aggregates is used in the Excess Paste Theory. It is easy to understand that the thickness of the excess paste around the sand particles can be calculated dividing the volume of excess paste by the total surface area. However, it is difficult to measure the correct value of specific surface area because it is affected by the size distribution and particle shape of the sand [8]. One should separately consider the influence of the size distribution and the particle shape on the specific surface area. Moreover, the thickness of the excess paste calculated from the specific surface area is physically different from the one calculated from the diameter of the particles. It is not possible to flatten out a sphere. For this reason, the particles' diameter measured by sieves or a laser diffraction instrument was used for the Water (Paste) Layer Model.

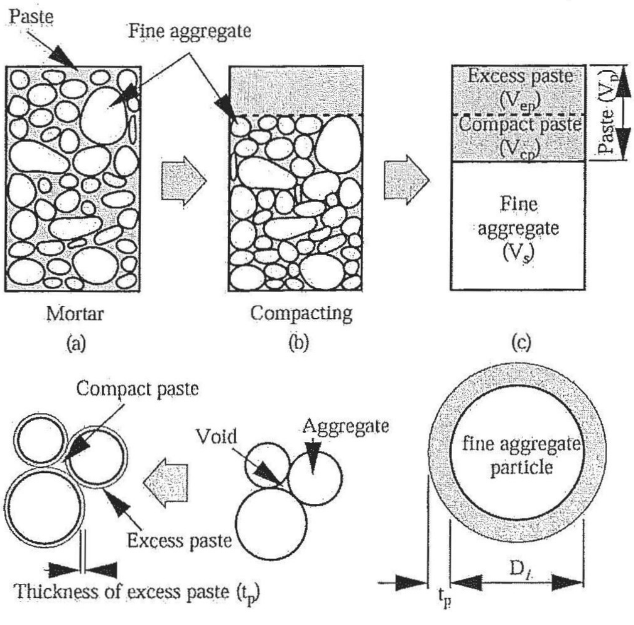

Figure 11: Excess paste theory [9]

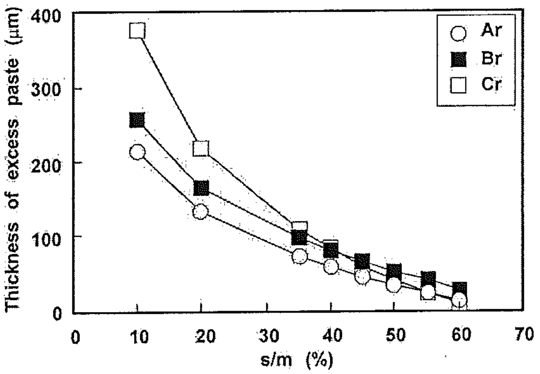

Figure 12: Comparison of the thickness of excess paste with different fine aggregate

So far, two assumptions are made:

1. The shape of the sand particles is spherical. The river sands that were used during the experiments were almost spherical. The shape of the sand can be modelled as an ellipse, a square or a rectangle, independent of the size distribution.
2. The thickness of the excess paste around the sand particles is the same for different sizes. Because the sand particles are uniformly dispersed in the mortar, the distance between the surface of the particles is constant.
   The calculating procedure of the thickness of the excess paste using the Water layer model is the following. The excess paste volume surrounding one particle of a size *i* (V_{epi1}) is calculated by Equation 2.

$$V_{\text{epi1}} = \frac{1}{6}\pi\left\{ \left(D_i + 2t_{\text{p}}\right)^3 \pm D_i^3 \right\} \tag{2}$$

where D_i is the diameter of a particle of a size *i*, *t*, is the thickness of the excess paste. The numbers of a particle of a size *i* can be counted from the size distribution of the sand. The excess paste volume of a size *i* (V_{epi}) can be calculated by Equation 3:

$$V_{\text{epi}} = \frac{1}{6}\pi\left\{ \left(D_i + 2t_{\text{p}}\right)^3 \pm D_i^3 \right\}\eta_i \tag{3}$$

where η_i , is the number of particles of a size i. The total volume of the excess paste (V_{ep}) can be calculated by summing up the volume of the whole grading, as shown in Equation 4,

$$V_{\text{ep}} = \sum_{i=1}^{n} \frac{1}{6} \pi \left\{ \left(D_i + 2t_{\text{p}} \right)^3 \pm D_i^3 \right\} \eta_i \qquad (4)$$

The excess paste layer is calculated by dividing the excess past volume by the surface area of the aggregate particles. The result is shown in Figure 12 for Ar, Br and Cr. The thickness of the excess paste layer becomes smaller if s/m increases. In addition, the thickness is larger for coarse sand than for a fine sand. The thickness of the excess paste layer depends on the solid volume and the size distribution of the sand.

Table 4 shows the results of the calculation of the thickness of the excess paste in μm. The compact paste volume is affected by the packing density of the sand. If the packing density of the sand increases, the compact paste volume decreases because the void volume between the sand particles decreases. Accordingly, the excess paste volume increases, and

*Table 4. Results of thickness of excess paste **

Type of sand	s/m (%)	Solid volume (%)	Sand volume (m^3/m^3)	Paste volume (m^3/m^3)	Compact paste volume (m^3/m^3)	Excess paste volume (m^3/m^3)	Thickness of excess paste layer (μm)
Ar	35	68.2	0.350	0.650	0.163	0.487	72.7
	40		0.400	0.600	0.187	0.413	58.8
	45		0.450	0.650	0.210	0.340	46.4
	50		0.500	0.500	0.233	0.267	35.1
	55		0.550	0.450	0.256	0.194	24.7
Br	10	71.6	0.100	0.900	0.040	0.860	257.7
	20		0.200	0.800	0.079	0.721	165.9
	35		0.350	0.650	0.139	0.511	97.7
	40		0.400	0.600	0.159	0.441	81.4
	48		0.450	0.550	0.178	0.372	66.6
	50		0.500	0.500	0.198	0.302	53.0
	55		0.550	0.450	0.218	0.232	40.2
	60		0.600	0.400	0.238	0.162	27.8
Cr	10	62.7	0.100	0.900	0.059	0.841	377.2
	20		0.200	0.800	0.119	0.681	218.2
	35		0.350	0.650	0.208	0.442	107.4
	40		0.400	0.600	0.238	0.362	82.4
	45		0.450	0.550	0.268	0.282	60.7
	50		0.500	0.500	0.297	0.203	41.4

*air content = 0%

the thickness of the excess paste becomes larger. During the experiments, the packing density of the sand was measured conform to JIS A 1104-1999. The resulting thickness of the excess paste differs depending on the manner of measuring the packing density. Figure 13 and Figure 14 show the relationship between the thickness of the excess paste layer and V_w/V_p, and the relationship between the thickness of the excess paste layer and SP/P, respectively. To make a mortar with the same fresh properties, V_w/V_p and SP/P should be increased if the thickness of the excess paste decreases. This is necessary because the collision and the friction between the sand particles in the mortar increase if the thickness of the excess paste decreases.

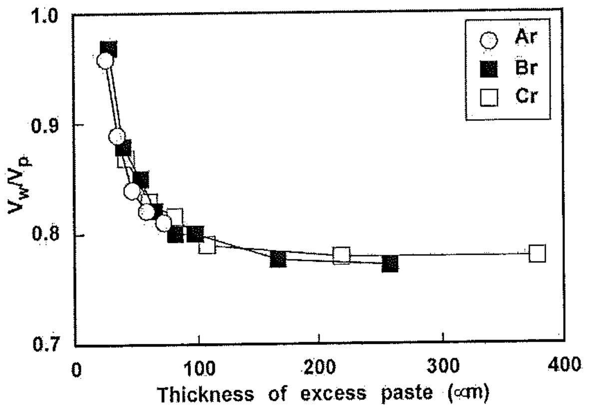

Figure 13: Relationship between the thickness of the excess paste and water to powder volume ratio

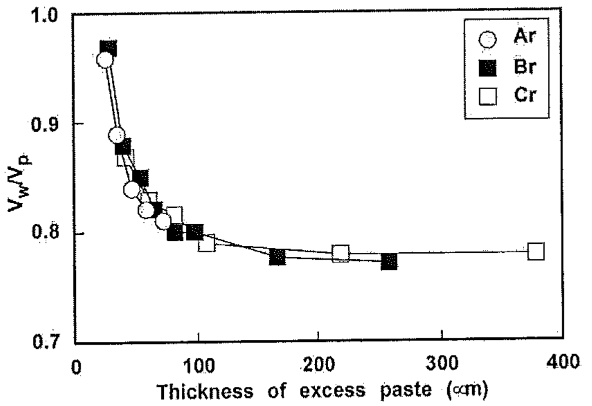

Figure 14: Relationship between the thickness of the excess paste and superplasticizer content

V_W/V_P and SP/P should be increased in order to avoid additional collision and friction. However, in spite of using different size distributions of the sand in this experiment, if the thickness of the excess paste layer is the same, V_W/V_P is also the same. If the thickness of the excess paste is the same, the probability of collision and friction is also the same because the distance between the sand particles would be the same. From this phenomenon, the amount of water from the thickness of the excess paste can be calculated. However, SP/P differs from case to case, so that it is not possible to calculate the superplasticizer content from Figure 14.

So far, we can describe the task of water and superplasticizer as follows. The task of water is to keep the distance between the cement particles or flocks (a fine powder flocculates easily under water, and it forms flocks). The distance between the cement particles increases if the content of water increases, and it decreases if the content of water decreases. On the other hand, the task of the superplasticizer is to disperse cement flocks. The flocked cement particles are dispersed if a superplasticizer is added. Similarly, the dispersion of the cement particles is affected by the size distribution of sand, the sand content, the mixing method and the kind of superplasticizer. If we use a sand with a suitable size distribution and a suitable sand content, the superplasticizer content might be lower. Therefore, the difference of SP/P shown in Figure 14 may be the reason for the different states of dispersion of cement particles, with the same distance between the cement particles. The characteristics of the paste could be the same if the thickness of the excess paste would be the same. To measure the characteristics adequately a viscometer for paste would be necessary.

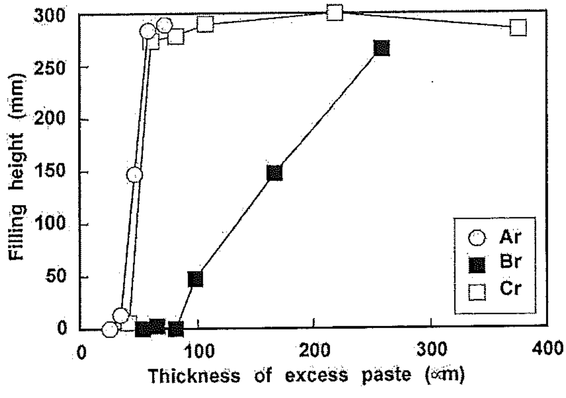

Figure l5: Relationship between the thickness of the excess paste and filling height

The fresh properties of the paste vary due to different distances between particle surfaces and a different dispersion degree of the cement particles. In case of adding the superplasticizer at a constant water volume, the cement particles are dispersed, and the distance between the cement particles is decreased. In other words, if the superplasticizer is added at a constant distance between the cement particles, the cement particles are dispersed, and the quantity of water has to be increased. To proof this is one of the purposes of this study. In the next paragraph, this will be discussed in more detail.

Figure 15 shows the relationship between the thickness of the excess paste and the filling height. The filling capacities of Ar and Cr are almost the same although their grading differs. The thickness of the excess paste layer that leads to a sufficient filling capacity was about 55 μm. However, the filling capacity of Br is very low because a considerable percentage of the particles of Br has a larger diameter than the opening between the ceramic balls; this was discussed before. According to Fujiwara [9], a minimum distance of more than 2.414 times the diameter D has to be provided to allow passing of the particles (shown in Figure 16). The minimum opening diameter between the ceramic balls is 3.713 mm. So, sand particles with diameters smaller than 1.538 mm can pass the ceramic balls. The median diameters of the sand of Ar, Br and Cr are 0.636 mm, 1.587 mm and 0.707 mm, respectively. The median diameter of Br is larger than 1.538 mm. This explains why Br had a low filling capacity. Besides this phenomenon, the filling capacity is affected by the thickness of the excess paste layer.

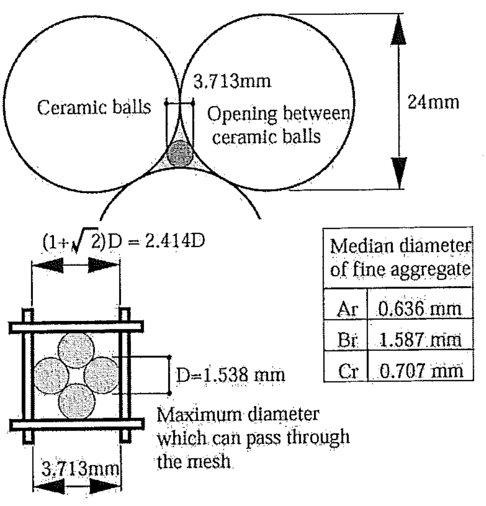

Figure 16: Comparison of particle diameter of fine aggregate passing ceramic balls [10]

4.3 *Investigation of the thickness of the excess water layer in self-compacting mortar*

In the previous paragraph, the influence of the thickness of the excess paste layer on the mix proportion of self-compacting mortar has been examined. It is supposed that a mortar consists of paste and fine aggregate according to the Excess Paste Theory, The relationship between the thickness of the excess paste layer and the properties of the mortar were explored. As a result, it has been clarified that V_w/V_p and SP/P should be increased if the thickness of the excess paste layer decreases in order to obtain self-compacting mortars with the same fresh properties. On the other hand, if we assume that mortar consists of water and solid materials, cement and fine aggregate, the relationship between the excess water and the mix proportion of the mortar may be examined using the principles of the Excess Paste Theory. In this paragraph, the results of the calculation of the thickness of excess water are presented, and the role of the water for self-compacting mortar is discussed.

Figure 17 shows the principal scheme for the calculation of excess water. Figure 17 (a) shows a sample of mortar in which water, cement and fine aggregate are uniformly dispersed. If it would be possible to squeeze out the water of the precipitation of cement and fine aggregate in mortar, the water could be divided into the compacted water, which has been placed between the solid particles and the excess water as shown in Figure 17 (b). According to F. de Larrard [10], the excess water can be calculated from the margin between V_w/V_p (β_m) in which the mortar begins to flow, and V_w/V_p of the target mortar. However, it is difficult to obtain the water retaining ratio β_m experimentally. Superplasticizer is abundantly added to self-compacting mortar; the deformation factor of mortar (E_m) is very small. Furthermore, segregation or bleeding does not occur under common

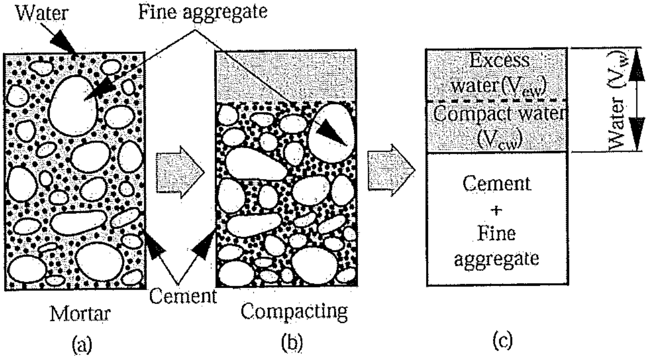

Figure 17: Principle of excess water

Circumstances because the content of water in self-compacting mortar is extremely low. The self-compacting mortars were separated into a solid and a liquid phase using centrifugal forces. The number of revolutions of the centrifuge was fixed throughout the experiments in order to avoid a variation of the excess water caused by centrifugal forces. The principle of the centrifugal separation was described before.

When the packing density of the solid materials of a unit mortar is P_s, the quantity of excess water (V_{ew}) can be calculated by Equation 5:

$$V_{ew} = \frac{\dfrac{1 \pm s/m}{1 + V_w / V_p} + s/m}{P_s} \tag{5}$$

where V_w / V_p is the water to powder volume ratio and s/m is the volume fraction of the fine aggregate in the mortar. It is assumed that the layer of excess water that surrounds the solid particles has a constant thickness. The total quantity of the excess water is obtained by summing up the whole quantity of the excess water of all single particles as shown in Equation 6:

$$V_{ew} = \sum_{i=1}^{n} \frac{1}{6} \pi \left\{ \left(D_i + 2t_w \right)^3 \pm D_i^3 \right\} \eta_i \tag{6}$$

where D_i is the diameter of the solid particles of a size i, η_i is the number of the solid particles of a size i and t_w is the thickness of the excess water layer. The thickness of excess water can be calculated from the size distribution of the solid particles, V_w / V_p and the packing density of the solid materials to satisfy Equation 6.

Table 5 shows the results of the calculation of the thickness of the excess water layer for all mortars. The largest part of water of each mortar is placed between the solid particles, the quantity of excess water is about 2% at a unit mortar volume only. This is rather low. This is the reason why only little water is required to provide sufficient fluidity for self-compacting mortar in the case that a superplasticizer is added.

The comparison of the thickness of the excess water layer for each mortar is given in Figure 18. When we gradually increase the fine aggregate content in the mortar (starting from s/m = 0%), the thickness of the excess water layer approximates a minimum. However the thickness of the excess water increases again with increasing ratio s/m. The figure shows that there is an optimum ration s/m at which the distance between the particles reaches a minimum. The quantity of the excess water necessary to achieve self-compacting properties of the mortar increases if s/m is higher or lower than the optimum value. Besides, the optimum ratio s/m changes slightly if the fineness modulus (F.M.) of the fine aggregate increases. In these experimental series, it was difficult to achieve the target V-funnel time using a mortar with a low s/m (in the case of s/m = 0 and 10%). It was also difficult to achieve a target flow value using a mortar with a higher s/m (in case s/m ≥ 35%).

*Table 5. Results of thickness of excess water**

Type of sand	s/m (%)	V_w/V_p	Packing density	Sand volume (m^3/m^3)	Cement volume (m^3/m^3)	Water volume (m^3/m^3)	Compact water volume (m^3/m^3)	Excess water volume (m^3/m^3)	Thickness of excess water (μm)
Paste	-	0.780	0.584	-	0.562	0.438	0.400	0.038	0.046
Ar	35	0.810	0.725	0.360	0.359	0.291	0.269	0.022	0.041
	40	0.820	0.744	0.400	0.330	0.270	0.251	0.019	0.039
	45	0.840	0.763	0.450	0.299	0.251	0.233	0.018	0.041
	50	0.890	0.780	0.500	0.265	0.235	0.216	0.020	0.049
	55	0.960	0.796	0.550	0.230	0.220	0.200	0.021	0.058
Br	10	0.780	0.623	0.100	0.506	0.394	0.366	0.028	0.038
	20	0.785	0.663	0.200	0.448	0.352	0.329	0.022	0.034
	35	0.800	0.725	0.350	0.361	0.289	0.270	0.019	0.036
	40	0.800	0.748	0.400	0.333	0.267	0.247	0.020	0.040
	45	0.820	0.766	0.450	0.302	0.248	0.230	0.018	0.040
	50	0.850	0.785	0.500	0.270	0.230	0.211	0.019	0.046
	55	0.880	0.805	0.550	0.239	0.211	0.191	0.019	0.053
	60	0.970	0.823	0.600	0.203	0.197	0.173	0.024	0.076
Cr	10	0.779	0.624	0.100	0.506	0.394	0.365	0.029	0.039
	20	0.780	0.666	0.200	0.449	0.351	0.326	0.025	0.038
	35	0.790	0.730	0.350	0.363	0.287	0.264	0.023	0.043
	40	0.815	0.748	0.400	0.331	0.269	0.246	0.023	0.047
	45	0.830	0.768	0.450	0.301	0.249	0.227	0.023	0.050
	50	0.870	0.787	0.500	0.267	0.233	0.208	0.025	0.061

* air content = 0%

In other words, if the sand content of the mortar is low, the critical property is the viscosity, but if the sand content is high, the critical property is the yield value. From this experience, the following is concluded: when s/m is low, then the paste volume would be high and the viscosity of the mortar surpasses the yield value; when s/m is high, the sand volume would be high and the yield value of the mortar surpasses the viscosity. If the viscosity and the yield value of the mortar are balanced, the thickness of the excess water layer has its minimum value. The thickness of the excess water layer has to be increased in order to decrease the viscosity or the yield value as shown in Figure 19(a).

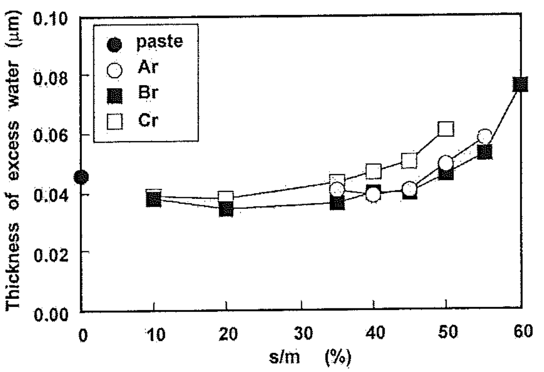

Figure 18: Relationship between thickness of excess water end s/m

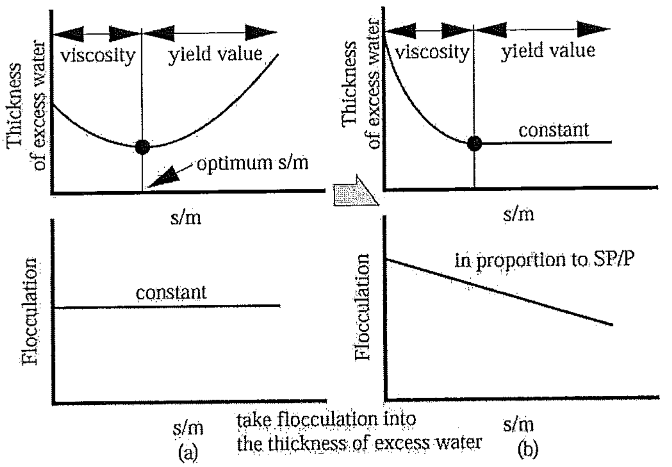

Figure 19: Assumption about the thickness of excess water

On the other hand, superplasticizers, not water, is added to decrease the yield value, and to increase the flow spread. The powder particles flocculate under water: if a superplasticizer is added, they would be dispersed. However, flocculation of cement particles was not considered in Equation 6 and Figure 18. The relationship between the content of superplasticizer and the dispersion of cement particles was not taken into account. Cement particles may be more dispersed at a higher content of superplasticizer. The superplasticizer content was higher with increasing s/m. If the thickness of the excess water would be fixed, V_W / V_p of the mortar should be increased when the cement particles are dispersed. In other words, the thickness of the excess water layer may be fixed considering the dispersion of the cement particles in Equation 6 as shown in Figure 19(b).

4.4 *Application and confirmation of the Water Layer Model to self-compacting mortar*

In the previous considerations, it was suggested to fix the thickness of the water layer at higher s/m values in the case that the cement particles are dispersed by the addition of a superplasticizer. In this section, the Water Layer Model is applied to these mortars. The dispersion of cement particles and the thickness of the excess water layer are further investigated.

The scheme of calculation of the thickness of the excess water layer using the Water Layer Model is almost the same as the manner using the Excess Paste Theory that has previously been discussed. However, the flocculation of powder particles is not considered in the Excess Paste Theory. Therefore this theory was extended to a model named the "Water Layer Model", which can take the flocculation into account. The consideration of flocculation is the peculiarity of this model. The basic assumptions about flocculation of the powder are laid down as follows (Figure 20).

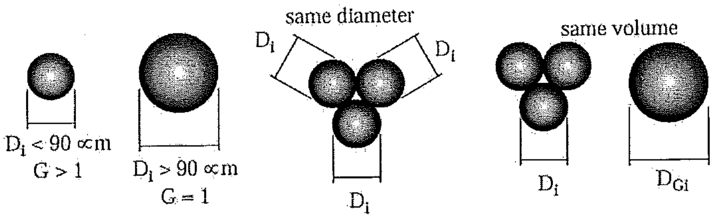

Figure 20: Basic assumptions about flocculation

1. Flocculation occurs for particles at a diameter below 90 µm [11].
2. The powder particles flocculate with particles of the same diameter,
3. The flocculated particles are considered as separated particles of a larger diameter, but of the same volume.

Different types of flocculation exist, smaller particles stick around larger particles, and smaller particles get together. Not many details about this are known till now. However, the characteristics of particles below a diameter of 90 µm are quite different from that above 90 µm. Moreover, the number of particles increases if the particles diameter decreases, so the probability that particles encounter each other becomes higher.

In the case some particles do flocculate, the volume of one flock (V_{sf}) can be calculated by Equation 7.

$$V_{sf} = \frac{1}{6}\pi \left(D_i\right)^3 G \tag{7}$$

where D_i is the diameter of the particles of a size i and G is the flocculation number of one flock. If the diameter of the particles is larger than 90 µm, G is assumed to be equal to one. The diameter of a particle with the same volume of a flock (D_{Gi}) is calculated by Equation 8:

$$G_{Gi} = \left(D_i^3 \; G\right)^{1/3} \tag{8}$$

The number of flocks of a size i (n_{Gi}) is given by Equation 9:

$$n_{Gi} = \frac{n_i}{G} \tag{9}$$

where n_i is the number of particles of size i. It is assumed that the thickness of the excess water layer around the particles is fixed, and the total quantity of excess water is calculated by summing up the volume of all particles. The relationship between the total quantity of the excess water and the thickness of the excess water layer is given by Equation 10.

$$V_{\mathrm{ew}} = \sum_{i=1}^{n} \frac{1}{6}\pi \left\{\left(D_{Gi} + 2t_{\mathrm{w}}\right)^3 \pm D_{Gi}^3\right\} \eta_{Gi} \tag{10}$$

where t_{w} is the thickness of the excess water layer. Therefore, the flocculation number (G) can be calculated to satisfy Equation 10 using the mix proportion of mortar and the size distribution of the solid particles.

Table 6 shows the flocculation number of particles with a diameter below 90 µm. The thickness of the excess water layer was set at 0.15 µm as a standard for the calculation; the thickness of the excess water layer is 0.16 µm if the flocculation number, for s/m = 60% for Br, is assumed to be 10. This assumed thickness is needed to calculate the relative flocculation number; it is not necessary to have an accurate value. The relationship between s/m and the flocculation number is given in Figure 21. The flocculation number decreases if s/m and the content of superplasticizer increases. The flocculation number shows a good

Table 6. Flocculation number for particles smaller than 90 μm*

Type of sand	s/m (%)	V_w/V_p	Packing density	Sand volume (m^3/m^3)	Cement volume (m^3/m^3)	Water volume (m^3/m^3)	Compact water volume (m^3/m^3)	Excess water volume (m^3/m^3)	Thickness of excess water (μm)	Flocculation number
Paste	-	0.780	0.584	-	0.562	0.438	0.400	0.038		-
	35	0.810	0.725	0.350	0.359	0.291	0.269	0.022		51.5
	40	0.820	0.744	0.400	0.330	0.270	0.251	0.019		59.7
Ar	45	0.840	0.763	0.450	0.299	0.251	0.233	0.018		52.0
	50	0.890	0.780	0.500	0.265	0.235	0.216	0.020		30.5
	55	0.960	0.796	0.550	0.230	0.220	0.200	0.021		18.6
	10	0.780	0.623	0.100	0.506	0.394	0.366	0.028		-
	20	0.785	0.663	0.200	0.448	0.351	0.329	0.022		86.4
	35	0.800	0.725	0.350	0.361	0.289	0.270	0.019		74.5
Br	40	0.800	0.748	0.400	0.333	0.267	0.247	0.020	0.150	56.4
	45	0.820	0.766	0.450	0.302	0.248	0.230	0.018		55.1
	50	0.850	0.785	0.500	0.270	0.230	0.211	0.019		36.2
	55	0.880	0.805	0.550	0.239	0.211	0.191	0.019		23.6
	60	0.970	0.823	0.600	0.203	0.197	0.173	0.024		8.2
	10	0.779	0.624	0.100	0.506	0.394	0.365	0.029		-
	20	0.780	0.666	0.200	0.449	0.351	0.326	0.025		64.3
Cr	35	0.790	0.730	0.350	0.363	0.287	0.264	0.023		44.5
	40	0.815	0.748	0.400	0.331	0.269	0.246	0.023		33.7
	45	0.830	0.768	0.450	0.301	0.250	0.227	0.023		28.0
	50	0.870	0.787	0.500	0.267	0.233	0.208	0.025		15.7

* air content = 0%

correlation with the content of superplasticizer as shown in Figure 22. As shown in this figure, the tendency to flocculate depends on the type of sand, that is characterized by its size distribution.

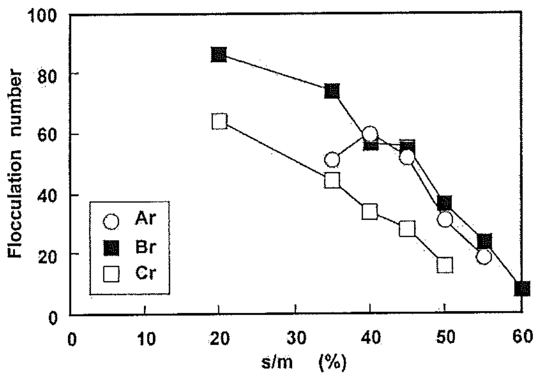

Figure 21: Relationship between s/m and the flocculation number

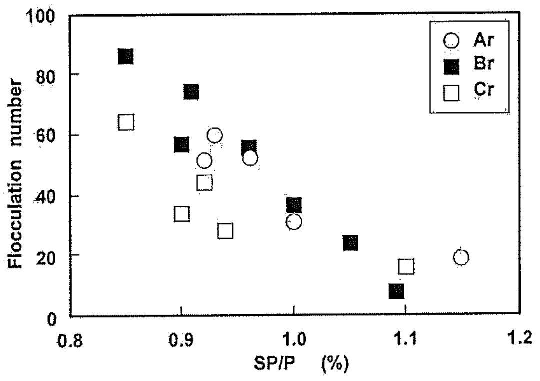

Figure 22: Relationship between content of superplasticizer and flocculation number

Finally, a relationship is assumed between the content of superplasticizer and the effect of powder dispersion as shown in Figure 22. Based on this phenomenon we can summarize the role of water and superplasticizer as follows: On the one hand, the viscosity is affected by the distance between solid particles or flocks; the thickness of the excess water layer has to be increased in order to decrease the viscosity. On the other hand, the yield value is affected by the dispersion of particles; the superplasticizer is added in order to decrease the yield value. Self-compacting mortar should have a compatible viscosity and yield value. The solid particles should be dispersed due to keeping the distance between the particles.

5 Concluding remarks

In order to extend the possibilities of the Water Layer Model, various experiments were carried out varying the mix proportions of self-compacting mortar. These mortars were prepared with fine aggregates at different size distributions and different volume contents. Based on this investigation, the following conclusions can be drawn:

1. V_W / V_P needed for self-compacting mortar increases with a decrease of the thickness of the excess paste layer. However, if the thickness of the excess paste layer is the same, V_W / V_P is also the same in spite of using different sands. Therefore, it is possible to obtain the amount of water needed for sell-compacting mortar from the thickness of the excess paste layer.
2. If the median diameter of the fine aggregate is small enough to pass obstacles, the filling capacity of mortar is correlated with the thickness of the excess paste layer. If the thickness of the excess paste layer is the same, the filling capacity is also the same for these

mortars in spite of having a different size distribution. The thickness of the excess paste layer needed to obtain the target filling capacity was about 55 μm in this study.

3. The characteristic of self-compacting mortar is divided into two patterns caused by different sand contents. One is the pattern that determines the viscosity, at a low ratio s/m, and the other is the pattern that determines the yield value, at a high value of s/m. This transition point was found at approximately 20% of s/m, but it is dependent on the size distribution of the sand.
4. It was possible to explain the role of water and superplasticizer using the Water Layer Model. The role of the water is to keep the distance between the particles, and the role of the superplasticizer is to disperse the particle flocks. Moreover, the distance between the particles that satisfies the properties of self-compacting mortar in the fresh state may be constant even if different sands are used.

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