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Preface

For decades little attention was given to the rheology of construction materials by civil engineers. Simple one point methods seemed to be sufficient for evaluating this “unimportant” phenomenon. The focus was on the properties of the final product.

When new constitutive materials entered the market, new construction materials and new production processes were developed. But even mixing technology changed. Mortar and concrete are stiff or soft suspensions with a yield point, thixotropy and grain sizes up to 32 mm, and are not that easy to evaluate as Newtonian liquids. Suddenly rheological data got more important. Self-compacting concrete and 3D-printing are examples for these developments.

New measuring tools and even very sophisticated and expensive rheometers are available now. For investigating the rheological parameters of cement bound materials, rheometers of different scale are used. Binder paste may be tested with rheometers intended for liquids, but for testing concrete with coarse aggregates special rheometers with no standard geometries have to be used. But how shall we use them? There are different types on the market, but it is difficult to compare their relative results. All will print nice graphs and precise numbers. But how reliable are this data? Moreover, absolute values are difficult to achieve. The main problems are particle migration, plug flow, wall slippage and often a geometry far from the classical plate-plate model. No certified calibration material for mortar and concrete is available at the time.

The problem from the material side is the time shear history and temperature dependent behaviour of all lime/gypsum/cement bound materials and the inhomogeneity of concrete with coarse aggregates. Shall we focus on optimised particle distribution or is it sufficient to use rheological admixtures for any mix? Portland cement is a robust binder in concrete, but in future the percentage in the ecological binders will be reduced.

The 26th Conference on the Rheology of Building Materials will give some answers to the mentioned questions regarding applied rheology and its application for different building and construction materials. The papers are collected in this proceedings. Beside the conference an interesting workshop took place in the new lab facilities of the faculty of civil engineering at the OTH Regensburg campus Galgenbergstrasse. After 25 years of rheological workshops the facilities in Prüfeninger Strasse are history now.

I would like to thank all lecturers and visitors as well as all members of the organizing committee for their support.

I am looking forward to meet you in Regensburg again.

Wolfgang Kusterle

Development of green self-compacting concrete containing low clinker cement and calcerous fly ash.

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Abstract

The paper presents a concept of shaping the properties of green self-compacting concrete (SCC), emphasizing mostly the minimization of the amount of clinker in concrete and obtainment of their low hardening temperature. The main purpose of this SCC concrete are massive and semi-massive constructions, as well as the constructions build during summer. Designed according to the proposed concept SCC are characterised by the low content of clinker, amounting from 60 to 77 kg/m^3 and good strength properties. It was proven that by optimizing materials and mix design one can obtain green SCC, characterized by low hardening heat and good mechanical properties in longer periods of hardening. Ground high-calcium fly ash can be used for self-compacting concrete, without negatively affecting its properties after hardening.

1 Introduction

The purpose of sustainable construction is to create and responsibly manage a healthy environment following the principles of environmental protection and efficient means. The responsible, sustainable production and use of construction materials represents one of the most important modern problems. Concrete, with its exceptional combination of functional and visual characteristics, is nowadays the primary construction material. Consequently, implementation sustainable development and sustainable construction principles into concrete designing, production and usage practice (into concrete construction live cycle) is particularly important.

One of the courses for such an action is to implement in practice the idea of green concrete. Green Concrete is defined as a concrete which uses waste material as at least one of its components, its production process does not lead to environmental destruction, and it has high performance and life cycle sustainability [1], [2]. In other way, Green Concrete is a term given to a concrete that has had extra steps taken in the mix design and placement to insure a sustainable structure and a long life cycle with a low maintenance surface. e.g. energy saving, CO_2 emissions, waste water. The key factors that are used to identify whether the concrete is green are: amount of Portland cement replacement materials (amount of clinker in concrete), manufacturing process and methods, performance and life cycle sustainability impacts.

The paper presents a concept of shaping the properties of green self-compacting concrete (SCC), emphasizing mostly the minimization of the amount of clinker in concrete and obtainment of their low hardening temperature. The main purpose of this SCC concrete are massive and semi-massive constructions, as well as the constructions build during summer.

2 The concept of green self-compacting concrete

The composition and constituents of SCC are chosen on the basis of appropriate rheological properties of the fresh concrete, taking under consideration the requirements for concrete in the construction. Fresh SCC has to fulfil following requirements: fluidity, which has to guarantee swift and precise filling of the form and covering of reinforcement, self-compaction, meaning its ability to quickly remove air from the mix, and lastly the stability, meaning the mix has to be resistant to segregation [3]. The reconcilement of the requirements of fluidity and self-compaction, namely obtaining a suitable rheological properties of the fresh concrete, is the biggest difficulty during the process of concrete designing. It is assumed, that for the sake of fluidity requirement the yield value of fresh concrete should be as low as possible. At the same time its plastic viscosity should be shaped so that the concrete mix properly and quickly fills the mould and to effectively remove air with a minimum segregation. The necessity to meet the rheological criteria determines the need for a specific composition and constituents of self-compacting concrete (Fig. 1). First and foremost, assumed are: small w/(c+a) ratio (w-water, c-cement, a - mineral additives), and a large amount of finest fraction (< 0.125 mm), which also includes cement and mineral additives (stone powder, ground granulated blast furnace slag, fly ash and others). Mineral additives increase the amount of cement paste without increasing the amount of cement over the necessary minimum. Due to the fact that presence of additives helps to reduce the amount of cement in the concrete mix, the amount of heat generated during the hydration is reduced. By properly choosing the type and amount of cement and additives it is possible to regulate the technical properties of concrete. Low w/c ratio and high content of finest fractions reduce the amount of free water in the mix increasing its resistance to segregation and sedimentation. The expected fluidity is obtained by use of effective PCE superplasticizers. Moreover, in order to lower the risk of segregation of the fresh concrete and obtaining its proper ability to flow, rounded, regularly shaped gravel is used; its maximal size should not exceed 20 mm and its sand content should be 40 ÷ 50%. In order to eliminate or reduce the segregation and the leakage of cement paste from the mix, and to lower its pressure on the formworks, it is recommended to use viscosity increasing admixtures. They also allow to improve the stability of the concrete mix without the need to interfere with its basic composition.

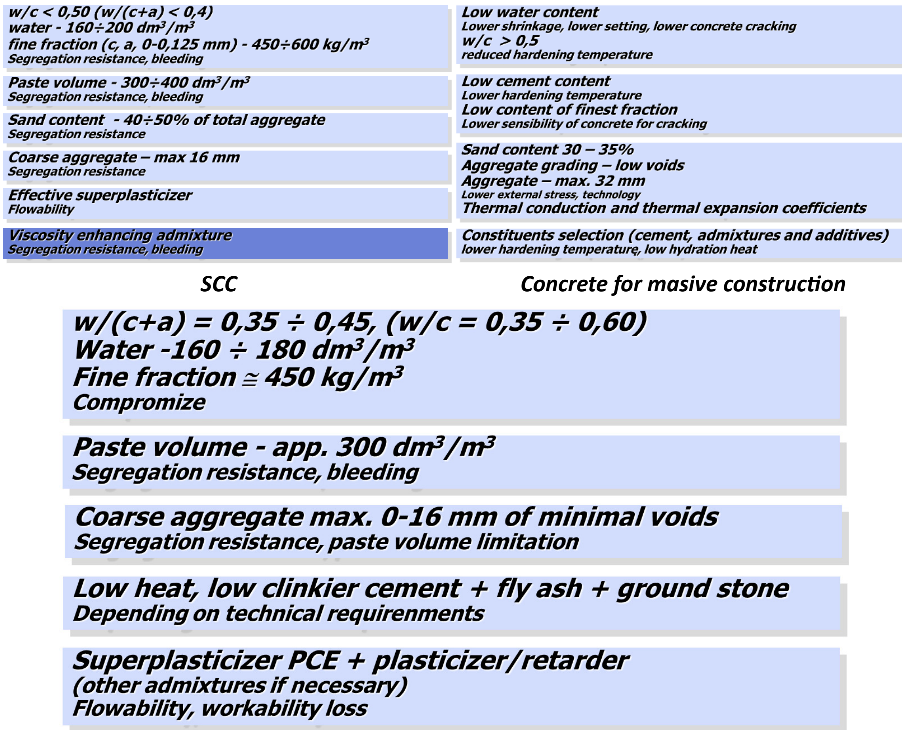

Figure. 1: Green SCC of low hydration heat concept

Proper selection of the constituents of the concrete mix is also essential for the suitability of building process of the massive construction (Fig. 1). The concrete composition is calculated so that the amount of heat generated by cement hydration is minimized, taking under consideration, of course, the requirements for concrete in construction [4]. Due to the fact that cement is a constituent determining the amount of generated heat, it is necessary to use the cements of low hydration heat and try to limit their content to the necessary minimum. In order to further limit the amount of generated head during the hardening of the concrete, as a substitute for the part of cement used are mineral additives - the best results are obtained by using fly ashes or ground granulated blast furnace slag. It is best to assume the w/(c+a) ratio lower than 0.5 (however, to reduce of the amount of generated heat to a minimum, w/c ratio can be higher). In order to delay the setting time and to spread the heat production in time, retarding admixtures are used. Due to the minimization of the amount of cement (and cement paste) it is beneficial to use aggregate of a biggest possible grain size and the amount of sand not higher than the 30-35%. It is worth noting that because of the technological factors and the possibility of causing tension in the element, aggregate grains should not be bigger than 31.5 mm.

The general concept of composition of SCC with low hydration heat is presented in Fig. 1. It was assumed, that the amount of the cement paste in this concrete should not exceed from 280 to 300 dm^3/m^3, meaning it should not diverge from the amount of cement paste in mechanically compacted concrete. For this amount of cement paste, by adequately choosing the w/c ratio, type and amount of cement and type of mineral additives, it is possible to more or less freely shape the rheological properties of the concrete mix, the amount of heat generated during the hardening and properties of the hardened concrete. It is also possible to fulfil the requirements from concrete standards that apply to the amount of cement (300 – 350 kg/m^3) and w/c ratio (0.45 – 0.60) which result from the exposition class dependant on the environmental conditions according to EN 206. If it is possible on the grounds of expected properties of hardened concrete, it is beneficial to set a possible high w/c ratio. The necessity of guaranteeing required stability of the SCC mix imposes the use of aggregate of maximal grain size of 16 mm. Use of gravel aggregate is an optimal choice considering the requirements for SCC and massive concrete. It was assumed, that required rheological properties of the concrete mix will be obtained by the use of carefully selected superplasticizer with retarding action, avoiding use of viscosity enhancing admixtures.

3 Experimental

During the research the possibility of obtaining the self-compacting concrete of low hydration heat according to the above mention requirements was verified. When selecting the amount and type of binder, it was sought to minimize the use of clinker in the concrete. Therefore, cement with low content of clinker CEM III was used (Table1). The amount of cement was also minimized by substituting it with calcareous fly ash (CFA) and/or limestone powder and/or silica powder. About 5 million tons of CFA is produced annually in Poland, as a result of brown coal combustion in conventional boilers. The results of studies [5] ad [6] show no negative influence of CFA on properties of hardened concrete. The main problem in practical use of CFS is, that its implementation significantly worsens workability of fresh concrete, especially in the aspect of workability loss. However, it was shown that the negative influence of CFA on the workability of fresh concrete may be reduced by processing it by grinding and even obtaining SCC with CFA is possible [4,5]. In the composition of concrete included were sand and gravel aggregate with the fraction grading shown in Fig. 2. SCC were designed using method presented in [7]. Properties of materials and concrete proportioning are shown in Tables 1 – 3.

Property		CEM I 52,5R	CEM III/B 42,5L-LH/SR/NA
Initial setting, min		144	204
Water for normal consistency, %		33	31.9
Volume stability, mm		0.7	0.7
Specific surface, cm^2/g		5032	5290
Hydration heat, J/g			225
LOI, %		1.28	0.86
SO_3, %		2.66	1.95
Na_2O_{eq}, %		0.66	0.70
Compressive strength, MPa	7 days	41.6	26.9
	28 days	66.5	55.3

Table 1: Cement properties

LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	CaO_w	Fineness, %		Volume mass, kg/m^3
							unprocessed	processed	
3.6	56.9	18.2	3.2	14.1	1.6	1.71	60.4	25	1058

Table 2: CFA properties

Ingredients [kg/m^3]	B0	B1	B2	B3	B4
CEM I 52.5	451				
CEM III/B 42.5		306	238	250	253
CFA			104		
Silica powder				135	
Limestone powder					125
Sand 0-4 mm	800	969	998	997	880
Coarse 4-11 mm	437	363	372	374	420
Coarse 8-16 mm	538	451	468	464	490
Water	171	193	151	158	160
SP	3.91	2.90	7.78	5.45	5.28
$w_{eff}/(c+a)$	0.38	0.63	0.44	0.41	0.42
w_{eff}/c	0.38	0.63	0.63	0.63	0.63
Cement paste volume, dm^3	320	294	270	293	291
Clinker content in concrete	428	77	60	62.5	63

Table 3: Concrete proportioning

Concrete	1h	2h	12h	24h	72h
B0	10.5 4	13.25	38.37	75.84	201.06
B1	8.95	10.92	22.70	32.31	151.64
B2	7.84	10.66	22.43	30.19	106.05
B3	6.70	8.41	13.31	19.69	81.83
B4	9.53	10.96	16.29	25.26	94.72

Table 4: Test results – cement + additive hydration heat [J/g]

Property		B0	B1	B2	B3	B4
Flow, mm	after 5 min	705	680	650	670	695
	after 60 min	680	670	600	660	670
Flow time T_{500}, s	after 5 min	2.3	2.7	6.0	5.2	5.4
	after 60 min	2.7	2.9	7.4	6.7	7.0
Air content, %		2,1	1.5	1.3	2.0	1.7
Setting time of concrete, h:min		6:36	10:04	12:00	10:12	9:43
Shrinkage after 24 h, mm/m		0,93	1.03	1.39	1.36	1.22
Maximal temperaturę, °C		72,9	34.8	32.2	30.0	32.2
Time of maximal teperature, h:min		18:54	36:55	51:28	45:56	43:56
Compressive strength, MPa	after 1 day	34.3	2.27	4.9	1.2	1.98
	after 7 days	58.6	25.4	36.0	31.0	29.4
	after 28 days	77.8	41.4	48.3	44.8	42.5

Table 5: Concrete properties

Concretes were tested for:

- Properties of fresh SCC - measurements were performed at a temperature 20°C at 5 and 60 min after the end of mixing using the slump-flow test according EN 12350-8. The stability of each mixture was evaluated with the Visual Stability Index (VSI; according to ACI 237 R-07; 2007). Additionally, the air content in the mixture at 5 min after the end of mixing was determined according to EN 12350-7.

- Setting time of concrete - measurements were performed using ultrasonic method by means of modified Schleibinger Vikasonik system. Transmitter and receiver were placed on the sides of beams 10x10x50 cm and tested for early shrinkage. Method is presented in details in [8].

- Development of concrete hardening temperature – measurements were performer on cubic samples 250 mm on a side insulated using styrofoam coating of thickness 100 mm and thermal conduction coefficient 0.044 W/mK. Temperature measurement was performed in the middle of cube. External temperature during the measurement was 20°C.

- Early shrinkage – measurements were performed using modified Schleibinger TLS apparatus on samples 10x10x50 cm during 24 hours from the moment of placement. During the test apparatus and samples were kept in climate chamber at a temperature 20°C and humidity of 60%. Method is presented in details in [8]. It is worth to note, that after 24 hours may be further tested for shrinkage using Amsler method.

- Compressive strength after 2, 7 and 28 days - measurement were performed according to PN-EN 12390-3. The samples were cured according to PN-EN 12390-2.

- Hydration heat - for binders and admixtures used in tested concretes hydration head and hydration kinetics were measured using isomeric calorimeter TamAir produced by TA Instruments. Measurement was held during 72 hours on binder paste with w/b and SP content analogous as in concrete at a temperature 20°C.

4 Test results and discussion

Obtained results are compiled in Tables 4 and 5.

The highest amount of generated heat during the hydration process obviously characterized B0 binder (Portland cement CEM I and SP). The other binders are characterized by significantly lower hydration heat and kinetics of its generation. The amount of generated heat is mainly dependent on the amount of cement clinker and specific surface. The smallest amount of heat was generated during the hydration of ground granulated blast-furnace slag cement CEM III/B 42.5 L-LH binders.

Self-compacting concretes of slump flow class SF2 and viscosity VF2 were obtained. Those properties are generally sustained on the stable level for at least one hour. This also applies to the concrete mixes which contain high-calcium fly ash (B4). In this case however it is necessary to increase the addition of superplasticizer. The concrete mixes are characterized by the air-content at the level of 2%. The use of CEM III/B and CEM III/B together with CFA and stone powders delays the setting time of concrete with reference to concrete with CEM I, and the delay amounts from 3 h to 5,5 h. Use of cement with mineral additives and mineral additives themselves has significantly lowered the maximal hardening temperature of concrete – from approx. 70ºC for concrete with cement CEM I to approx. 30ºC for concretes with CEM III/B. Using the cement CEM III/B is particularly effective, whereas using mineral additives with this cement influences the concrete temperature only to a smaller degree. Using the cement CEM III/B itself did not significantly affect the delay in reaching the maximal temperature of concrete in comparison to CEM I concrete. However, in case of using mineral admixtures as cement CEM III/B replacement the maximal temperature was recorded from 18 to 27 hours later than in the concrete with cement CEM I. Shrinkage after 24 h of CEM III/B concretes is higher than of reference concrete. The implementation of CFA of stone powders in place of part of cement increases shrinkage.

As it could be expected, the compressive strength after 2 days of concretes with cement CEM III/B and with the mineral additives is low and amounts approx. 1 to 5 MPa. However, after 7 days it amounts already 29 to 36 MPa, with the highest value for concrete containing CFA is achieved. After 28 days a compressive strength of 42 - 47 MPa for CEM III/B concretes was obtained (usually concrete class up to C30/37 is specified for concretes for massive constructions). Taking into account that the amount of clinker in tested concretes varies between 60 – 80 kg/m^3 (Table 5), obtained by them compressive strength should be considered as very satisfying.

It was reconfirmed that despite the negative influence on the workability, CFA which underwent the grinding process can be used for self-compacting concretes. Its presence either does not affect or affects positively remaining concrete properties.

5 Summary

Designed according to the proposed concept self-compacting concretes are characterised by the low content of clinker, amounting from 60 to 77 kg/m^3, and good strength properties. It can also be assumed that these concretes will also be characterised by the adequate durability due to the high content of blast-furnace slag. However, it requires further experimental verification.

It was proven that by optimizing materials and mix design one can obtain green self-compacting concrete, characterized by low hardening heat and good mechanical properties in longer periods of hardening. This kind of concrete performs well especially in massive and semi-massive elements.

Ground high-calcium fly ash can be used for self-compacting concrete without negatively affecting its properties after hardening.

6 Acknowledgements

The results presented in this paper have been obtained within the project ‘‘Innovative cement binders and concretes with addition of high calcium fly ash’’ (project no POIG,01,01,02-24- 005/09 with the Polish Ministry of Science and Higher Education) in the framework of the Operational Programme Innovative Economy 2007–2013.

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A Particle Distance Model for Self-Compacting Mortars and Concretes

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Abstract

Small variations in the water content of a concrete mix or in the water demand of the raw materials exert a decisive influence on the rheological properties of Self-Compacting Concrete (SCC). This effect is increased by the comparatively high amount of additions and the total binder content in these concretes, respectively. To analyse the effect of the water content on the rheological properties, a particle distance model was developed. It describes the relative viscosity as well as the gradient of the flow curve (linear, shear thickening or shear thinning behaviour) depending on the distance between the particles in the mix. Thus, the qualitative prediction of the rheological behaviour of an SCC is possible. For the rheological characterisation, self-compacting mortars were investigated with a rotational viscometer. The parameters investigated were the granulometry of the powder as well as the influence of the total water content of the mortars. For these examinations, ordinary Portland cements with different finenesses were applied. During the investigation programme mostly fly ashes were used as addition. They differ concerning their fineness and grain shape (dry or wet bottom furnace). One fly ash of each type was fractionated in defined grain size classes.

1 Introduction

During the practical application of Self-Compacting Concrete (SCC), it becomes obvious that rheological properties of an SCC which are of utmost importance for the self-compacting properties may vary very strongly. There are different reasons for these variations. On the one hand, it is well known that the fresh concrete temperature has an influence on the rheological properties [1]. On the other hand, small variations in the water content or in the water demand of the raw materials exert a decisive influence on the rheological properties of SCC. This effect is increased by the comparatively high amount of additions and the

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total binder content in these concretes, respectively. The total powder content can amount to approx. 620 kg/m³. To analyse the effect of the water content, i. e the solid concentration in the suspension, on the rheological properties, several approaches are described in literature conducting fundamental rheological studies. Within this paper, an approach with a developed particle distance model (PDM) is described. With this PDM, the relative viscosity as well as the flow behaviour (linear, shear thickening or shear thinning behaviour) i. e. the gradient of the flow curve depends on the distance between the particles in the mix. The investigations were conducted during research work at the Institute of Building Materials Research (ibac) of RWTH Aachen University.

With this PDM, the influence of the water content on the rheological properties of self-compacting mortars (SCM) is investigated. Thus, the qualitative prediction of the rheological behaviour of an SCC is possible.

2 Particle Distance Models for the Description of the Flow Behaviour of Mortars and Concretes

Investigations on the solids concentration are described in the literature for cement paste, mortar and concrete. Consistency tests on mortars and concrete, however, were conducted almost without exception applying so-called one-point methods. Here, a difference is always made between the consideration of a solid and a liquid phase.

Ferraris describes investigations where the solid phase is given by cement, aggregate and additions [2]. The liquid phase is only modelled by the water. Ferraris does not consider it permissible to make a separation between paste and aggregate since the size of the coarsest cement particles corresponds to that of the finest sand grains. Moreover, their contribution to the flow behaviour is not different as long as hydration is disregarded. The model is based on a model of Chang [3] which assumes that the plastic viscosity depends on the relative concentration of the solid particles.

If the relative viscosity is plotted against the relative solids concentration, an exponential course is obtained and the following semi-empirical equation to assess the plastic viscosity of concrete is found [2]:

$$\eta_{pl} = \exp\left(26.75\left(\frac{\varphi}{\varphi_{\max}} - 0.7448\right)\right)$$

This course was the same for all tests, independent if it were mortar or concrete tests and whether or not superplasticisers or additives were added.

If the yield stress is plotted against the solids concentration just as the plastic viscosity, then there is no such correlation. Here, it became necessary to take into account the grading of the particles. If superplasticisers are applied, higher solids concentrations are possible because the water demand of the solid phase decreases. The result is a lower yield stress.

Krell [4] characterizes the paste as liquid phase and the total aggregate as solid phase. The paste is attributed a filling, a lubricating and a sticking effect. Only after filling the voids, the lubricating effect of the paste starts since then the particles of the aggregate are pressed apart and a paste layer develops between the particles. Besides the lubricating effect, the particles are held together because of the surface forces of the water-solids mix. Apart from the paste properties, the described lubricating effect of the paste directly depends on the thickness of the paste layer between the aggregate. To calculate the thickness of the paste layer, the amount of paste remaining after all voids of the aggregate are filled is calculationally evenly distributed across the surface of the aggregate.

Bui [5] calculates the mean particle distance (cf. Figure 2.1) with the following formula:

$$D_{SS} = D_{av} \left\{ \sqrt[3]{1 + \frac{V_P - V_{oid}}{V_c - V_p}} - 1 \right\}$$

D_{SS}: average particle distance when a spherical shape is taken

V_P: paste volume

V_{oid}: void content in the compacted aggregate

V_C: volume of the concrete

D_{av}: average particle size

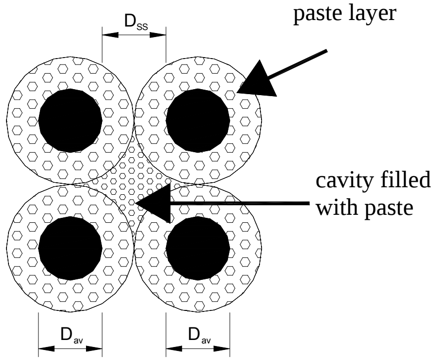

Fig. 2.1. Aggregate idealised as spherically shaped with the distance D_{SS} and the average particle size D_{av} according to [5]

This particle model has the disadvantage that the aggregate idealised as spherically shaped. Thus the effects of the particle shape are not integrated. Bui establishes a correlation between the particle distance and the relative viscosity but it is not specified in this context because it calculates the relative viscosity with the Bingham model [5]. The result was negative yield stresses which are physically impossible.

Oh [6] assumes a variable layer thickness of the paste on the aggregate (Figure 2.2).

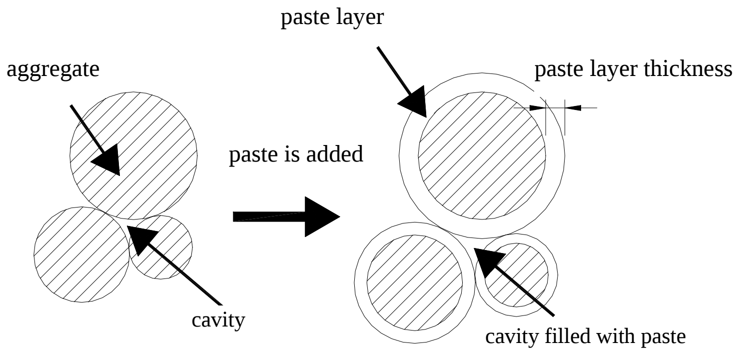

Fig. 2.2. Variable paste layer thickness on the aggregate according to [6]