Effect of water film thickness on the flow in conventional mortars and concrete

Y. Ghasemi · M. Emborg · A. Cwirzen

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Abstract Mortar and concrete can be divided into two phases of solids and water, where water fills the voids between the grains and also coats the surface of the particles. The current study investigates the influence of the thickness of coating water on flow spread of mortars and concrete. The article aims at correlating consistency of concrete to consistency of mortar using the concept of excess water layer theory. It was found that the flow behavior of granular mixtures can be directly related to the average water film thickness that envelops the particles. The concept was tested on mortars and concrete mixtures with different cement types, aggregate grading, aggregate shape, fineness and proportioning; proving water film thickness to be the most critical parameter affecting the flow. The results of the study indicate the possibility of predicting the flowability of mixtures by knowing the thickness of the water film that envelops the grains. In addition, the relation between flowability of mixtures measured in different sizes of slump cone is explored to enable translating flow of mortars measured in mini-slump cone to flow of concrete obtained from Abrams' cone.

Keywords Flowability · Excess water layer theory · Water film thickness · Mix design

1 Introduction

Researchers have made several attempts at formulating the flow behavior of fresh concrete. The workability of concrete, i.e. consistency, pumpability, flowability, etc. is of great importance when it comes to the daily production of mixtures based on a mix design model. Researchers often relate their formulation attempt to the science of rheology of fresh concrete and the parameters of the Bingham model, i.e. yield stress and plastic viscosity. The interest in investigating the rheology of mixtures has grown during the last decades especially on highly flowable mixtures like self-compacting concrete. Thus, it was found that the rheology of fresh concrete, in turn, is dependent mainly on the flow behavior of its mortar portion [1]. Moreover, it was found that the flowability of concrete increases with flowability of its mortar portion [2]. Thus, the relation between the flowability of concrete and mortar implies that it is possible to understand the flow behavior of a concrete mixture by studying its mortar. However, this involves issues related to upscaling the flow behavior of mortars to concrete including and not limited to the effect of measurement method and difference in the efficiency

Y. Ghasemi (✉) · M. Emborg · A. Cwirzen
Department of Civil, Environmental and Natural
Resources Engineering, Luleå University of Technology,
Luleå, Sweden
e-mail: Yahya.ghasemi@ltu.se

M. Emborg
Betongindustri AB, Stockholm, Sweden

of mixers used for making mortars versus concrete. The number of studies that can explain the relationship between flow behavior and consistency of mortars to concrete is scarce.

Most of the literature concerning flowability of cementitious mixtures focus on the relationship between water to cement ratio or water content to the flow of the blends. Utilizing water content or water to cement ratio dismisses the roles of packing density and fineness of constituents. The correlation between the flow of mortars and concrete can be improved by investigating the flowability of the mixtures using excess water layer theory.

Cementitious mixtures in the fresh state can be seen as a two-phase suspension where particles are enveloped by a layer of excess water that reduces friction in aggregate skeleton by separating and lubricating those particles [3, 4]. In this way, by dividing the volume of excess water to the specific surface area of aggregates, an average water film thickness is obtained that can be related to the flow of mixtures, as described later in this article.

Throughout the years, several studies were conducted on the effect of water film thickness on the flow behavior of mixtures where strong relationships were found between both yield stress and viscosity of mixtures and the flow [3–7]. For instance, Kwan and Li [8] concluded that the main factors affecting the rheology of granular mixtures are the water content, the specific surface area of particles and packing density, factors that are implemented in water film thickness value. The key role of water film thickness in rheology of mixtures is also confirmed by other researchers [9, 10].

The primary purpose of the article is to study the relationship between the consistency of conventional mortar and concrete through the concept of water film thickness. The available literature concerning the subject commonly covers mixtures with larger specific surface area (applicable to self-compacting concrete or powder rich mortars) due to high volumetric share of finer particles.

Therefore, in this work, it was decided to limit the range of specific surface area to the applicable range in the production of conventional mortars and concrete which is several times lower than that of the studied materials in the literature. Moreover, concrete mixtures studied in the literature mostly include superplasticizer which makes it difficult to compare the flow

of concrete with mortars containing no superplasticizer. Additionally, compaction energy introduced to mortars and concretes is not equal since concrete mixers generally apply more energy to the blends comparing to mixers used for mortars. Furthermore, the spread of mortars and concretes are measured in molds with different geometry which enforces an additional factor in the comparison of flow of mortars versus concrete. Influence of both compaction energy and geometry of slump cones are discussed in the following sections.

The study provides a foundation for estimating the flowability of mixtures based on simple input data, i.e. packing density and specific surface area. The authors inspected the following hypotheses in the paper:

- Water demand of granular mixtures to be put at the onset of flow, that is the state where the voids between the particles are filled and an additional water film wetted the surfaces of the grain, is related to the specific surface area of particles as well as packing density of matrix.
- Amount of water required to increase the diameter of flow spread measured by a slump cone is related to the total surface area of solids available in the mixtures.

The following conditions were assumed for calculating the amount of excess water:

1. Particles have uniform shapes. A necessary assumption for calculating the specific surface area based on particle size distribution. In the current study dodecahedron and cube were chosen as the representative shapes for natural aggregates and crushed, angular particles respectively.
2. Water film thickness is calculated as an average with the assumption that the film thickness is equal for particles with different sizes.
3. All the particles are homogeneously distributed in the blend with no segregation or agglomeration occurrence.

2 Methods and theories

The effect of water content on the flowability of mixtures has been extensively studied by many researchers [11–14]. Most of the times the volume of water or w/c ratio is compared with the flow of

mixtures employing flowability measures such as slump, flow spread, etc. and/or rheological parameters, i.e. yield stress and viscosity. However, mixtures with the same flowability can have different water content depending on the characteristics of constituents in the mix [12]. Even for the same w/c ratio and cement content, the rheological characters of concrete and mortars change when the condition of aggregates such as particle size distribution or proportions are altered [3]. Hence, the thickness of water film that covers the surface of particles is a better parameter for relating the flowability of blends compared to the water content in the mixtures since the parameter includes the effect of shape and surface area of the particles. According to excess water layer theory, mixtures with the same specific surface area (SSA) require similar water film thickness to achieve a certain flow. The theories and methods used in this study are further described in the following sections.

2.1 Excess water layer theory

Fresh concrete is considered to be composed of aggregates and paste. A certain amount of paste is required to fill the voids between the aggregates; at this point, the mixture is not workable and has no flow. However, the addition of excess paste separates the aggregates and acts as a lubricant among the particles of aggregates [15].

The paste itself is composed of cement, possibly fine particles and water. In a similar concept, cementitious mixtures can be seen as a suspension of solid particles in water, see Fig. 1. This water can be divided into:

Fig. 1 Schematic illustration of void filling and excess water [25]

1. Water that fills the spaces among the particles of cement and aggregates (W_{vo}) which is related to packing density of solids in the mixture. A mixture containing only W_{vo} exhibits no slump and additional water is required for governing the flow, see Fig. 2.
2. Excess water (W_{ex}) that coats the surfaces of particles, separating and reducing friction inside the particles' skeleton. The excess water can be alienated into two parts as well:
 - a. Excess water that is required to put a mixture at the onset of flow (W_{on}).
 - b. Excess water required for governing a certain flow of the mixture (W_{re}).

Mix design approaches that are mainly based on particle packing theory focus on the effect of void filling water and dismiss the importance of excess water influence on the flow of mixtures. Mix design models strive for a higher packing in mixtures and hence lower void content, which is usually obtained by introducing fine particles to the blend. In this case, while the amount of void filling water decreases, more excess water is required for covering the large surfaces of fine particles. According to [16], the increase in packing density and SSA have counter effects on the flowability of mixtures. The suggested approach in this study considers the effects of both void filling water (1—loose packing density) and the excess water (related to SSA), details of which is introduced in Sect. 2.1.2.

The effect of excess water can be studied through the concept of water film thickness, that is the average thickness of water film that covers the surface of aggregates and is calculated by dividing the volume of excess water by surface area of solid constituents in the mixture indicating the importance of accurate estimation of SSA.

2.1.1 Specific surface area (SSA)

Effect of the surface area of particles in cementitious mixtures has been widely discussed by scientists and concrete engineers [17–20]. While the researchers agree on the importance of the parameter, an accurate general measuring method is yet to be developed. The Blaine test method [21] can be used for measuring the surface area of cement but not necessarily other powders, and results from the BET test [22] includes

Fig. 2 Schematic relationship between relative slump and water to solids ratio [25]

the surface area of open inner pores in the particles. Consequently, Blaine and BET values for the same material can be entirely different [23].

A common approach to estimating the value of SSA for granular materials is by calculation based on the particle size distribution curve and assuming spherical shapes for the grains. Alternatively, the authors [24, 25] previously suggested replacing the assumption of spheres with dodecahedra and cubical shaped particles for natural and crushed aggregates respectively which has shown to improve the estimated value by accounting for angularity of natural and crushed materials [24, 25]. Thus, in the current study SSAs of aggregates were calculated based on their particle size distribution and assumption of dodecahedron and cube shapes using the method discussed in [24] where results were justified by comparison to the values obtained from X-ray microtomography method. In this article, the Blaine values were used as SSA for different types of cement.

2.1.2 Water film thickness

In order to determine the water film thickness (WFT), the packing density of solid constituents should be known. This can be achieved either by lab measurements and/or using packing models. The current study utilizes the modified Toufar model [26] for calculating the combined packing densities of particles due to acceptable accuracy and simplicity of the model. Packing density can be measured in wet, loose, vibrated and compact state. Loose packing [27] was chosen for conducting studies of packing density as the reference value due to simplicity of the measurements. In addition, the extent of the effect of applying

compaction on a packed material depends on many factors including shape and the fineness of particles [28]. In that sense, measuring the packing densities using hard packing methods introduces another uncertainty to the method. It should be mentioned that it is also possible to measure the packing in wet state, however, again the ratio between the packing density in loose state and wet state dependent on particle size distribution, shape and fineness of the material. Moreover, packing models with accepted accuracy exist for estimating the combined packing of different fractions in dry state [26] while in case of wet packing, the values should be measured.

The volume of excess water can be obtained by subtracting void filling water (W_{vo}) from the total amount of water for a unit volume of particles (W_{tot}), the volume of void filling itself is equal to the void content of the particle's skeleton:

$$W_{vo} = 1 - \phi_{Loose} \quad (1)$$

$$W_{ex} = W_{tot} - W_{vo} \quad (2)$$

where ϕ_{Loose} is packing density of particles in the loose state. With known SSA and excess water volume, the WFT can be simply obtained by dividing excess water volume by surface area of particles in the mixture.

As mentioned earlier, excess water can be divided into excess water required for initiation of flow (W_{on}) and excess water necessary for the continuation of flow (W_{re}):

$$W_{ex} = W_{on} + W_{re} \quad (3)$$

$$W_{re} = W_{tot} - \beta_w \quad (4)$$

The amount of water required to put the mixture at the onset of flow (W_{on}) for a unit volume of solids, in turn, can be obtained by:

$$W_{on} = \beta_w - W_{vo} \quad (5)$$

Water film thickness can be calculated for both at the onset of flow conditions as well as the flowing state according to:

$$WFT_{on} = \frac{W_{on}}{SA} \quad (6)$$

$$WFT_{re} = \frac{W_{re}}{SA} \quad (7)$$

where β_w is water retaining capacity of mixture and SA is the surface area of all the solid constituents in the mixture. Values of β_w and volumes of W_{on} and W_{re} were obtained by slump tests. In the case of mortars, a mini-slump cone is used for performing the flow test. However, for concrete, the tests were conducted using Abrams' cone.

In the slump tests, a cone is filled with the blend and the diameter of flow is measured once the cone is lifted, the relative slump, Γ , is then calculated based on:

$$\Gamma = \left[\left(\frac{d_1 + d_2}{2} \right) / d_0 \right]^2 - 1 \quad (8)$$

where d_1 and d_2 are the measured perpendicular diameters of spread and d_0 is the diameter of the bottom opening of the cone. By repeating the test with different volumes of water, a trendline similar to the one in Fig. 2 can be expected, showing variations in flowability of mortars with respect to volumetric changes in the water–solid ratio [18]. It should be mentioned that the introduced method and theories were developed for highly flowable over saturated mixtures like self-compacting concrete and as such includes measurement of flow spread rather than the slump. Moreover, analysis of flow for both mortar and self-compacting concrete is conducted with no extra compaction such as rodding or vibrating the material; however, measurement of the slump for conventional concrete includes compaction with rodding. In order to treat the results of all the test in the same manner, measurements of spread flow were conducted without applying additional compaction in the slump cone.

The interception of the trendline in Fig. 2 with the Y-axis, is called the water retaining capacity, β_w , and

shows the minimum water demand for putting the mixture at the onset of flow (zero slump, $\Gamma = 0$). The volume of water at the onset of flow is equal to void filling water (W_{vo}) plus water required for initiation of the flow (W_{on}).

Moreover, the slope of the trendline is called deformation coefficient, E_w , and indicates the sensitivity of the mixture on variation in water content for specified flowability. The coefficient represents the relative water requirement of mixtures for increasing the relative slump by a unit. The volume of water required for governing a certain flow (W_{re}) can be calculated by knowing the slope of the trendline and expected relative slump. According to Fig. 2, a linear relationship exists between the relative slump and water content as:

$$\frac{V_{Water}}{V_{Solid}} = \beta_w + E_w \Gamma \quad (9)$$

Mortars listed in Table 2 were made with at least three different water content to achieve a reliable trendline and consequently more accurate β_w and E_w , the relation was confirmed to be linear with coefficient of determination $R^2 > 0.9$ for all the tested materials. Each test is repeated at least twice. In the case of concrete, every three mixes with the same SSA were analyzed for obtaining water demand of mixtures, see Table 3.

3 Materials

To validate the relationship between specific surface area (SSA), the water film thickness (WFT) and flow of mortars and concrete, a series of 71 mortar and 26 concrete mixes were prepared and tested in the laboratory. The same type of coarse aggregate (8–16 mm) was used in all the concrete mixtures. Recipes were designed to have a specific surface area in the range of conventional concrete and mortars. The employed types of cement were produced by Cementa AB and Jehander AB supplied the aggregates as listed in Table 1. The packing densities were measured in the loose state according to [27]. Particle size distribution of aggregates and limestone were measured by dry sieving and laser diffraction particle size analyzer respectively. The sieving curves are presented in Fig. 3.

Table 1 Constituents of mixtures

Material	Relative density (g/cm ³)	Loose packing density (%)	SSA (cm ² /cm ³)
CEM I 42.5 N (Anläggning)	3.200	39	9920 ^a
CEM I 52.5 R (Skövde SH)	3.125	40	17187 ^a
CEM II 52.5 N (Bascement)	3.000	42	13500 ^a
CEM II 42.5 N (Anläggning FA)	3.017	42	11374 ^a
Limestone (Limus 40, Nordkalk)	2.700	41	11046 ^b
Natural 0–4 mm (Riksten)	2.702	60	154.17 ^b
Natural 0–1 mm (Riksten)	2.702	56	250 ^b
Cubic crushed 0–4 mm (Bro)	2.600	63	117.44 ^b
Cubic crushed 0–1 mm (Bro)	2.600	55	190.51 ^b
Cone crushed 0–4 mm (Jehander)	2.704	64	195.90 ^b
Cone crushed 0–1 mm (Jehander)	2.704	59	314.69 ^b
Mid-crushed 4–8 mm	2.600	53	16.84 ^b
Coarse 8–16 mm (Ledinge)	2.680	66	7.06 ^b

^aReported Blaine value by the producer^bCalculated based on particle size distribution [24] **Fig. 3** Particle size distribution of aggregates and limestone

3.1 Mixtures proportions

The studied mixtures were made using three types of cement and with variation in aggregate type, water to cement ratio and volumetric share of constituents. Proportions were decided based on their resulting SSA as calculated using particle size distribution and assumption of dodecahedron and cube as the uniform shape of natural and crushed aggregates, respectively [24]. the ingredients of mortars and concretes and their volumetric share are listed in Tables 2 and 3. Mortars mix ID is reported in the format of M#X where # is the test number and the letter represents the type of

aggregate used in the mortar, “R”, “B”, “J” stand for Riksten, Bro and Jehander, respectively. Each mixture was produced with at least three water content.

Concrete mixtures are designated mix ID in the format of C#X where blends with the same number have the same total SSA, and the letter represents different water content, see Table 3. Note that due to rounding of number, the sum of the volumetric share of constituents may slightly be lower or higher than 100%.

Mortars were prepared in 2 L batches using a Hobart mixer on low speed with the power rating of 120 W whereas a Zyklos mixer with power rate of 2.2 kW was utilized for production of 30 L batches of concrete.

4 Flowability measurements

Several approaches exist for evaluating the flow characteristics of cementitious mixtures among which, slump flow tests are the most practiced ones for designing workable mixtures. The method is preferred in the study due to its availability as an in situ, simple and cheap test. Slump tests are based on the fact that flow stops when shear stress in the tested sample becomes smaller than the plastic yield value [29].

Table 2 Mortars constituents and proportions

Mixture code	Cement		Fines (0–1 mm)		Calc. SSA cm ² /cm ³	Packing density %
	Type	Vol% of solids	Type	Vol% of solids		
M1R	I42.5N	20.01	Riksten	79.99	2162.64	63
M2B	I42.5N	18.84	Bro	81.16	2047.60	68
M3J	I42.5N	19.51	Jehander	80.49	2188.45	65
M4R	I42.5N	25.10	Riksten	74.90	2656.18	65
M5B	I42.5N	23.64	Bro	76.36	2512.77	67
M6J	I42.5N	24.42	Jehander	75.58	2660.50	64
M7R	I52.5R	15.84	Riksten	84.61	2832.78	60
M8B	I52.5R	14.85	Bro	85.15	2738.81	65
M9J	I52.5R	15.40	Jehander	84.60	2912.58	60
M10R	I52.5R	24.85	Riksten	75.15	4437.90	62
M11B	I52.5R	24.07	Bro	75.93	4303.59	67
M12J	I52.5R	24.86	Jehander	75.14	4509.57	66
M13R	I42.5N	36.11	Riksten	63.89	3723.66	63
M14B	I42.5N	35.14	Bro	64.86	3628.12	66
M15J	I42.5N	36.13	Jehander	63.87	3784.33	61
M16R	I52.5R	32.63	Riksten	67.37	5758.08	62
M17B	I52.5R	31.70	Bro	68.30	5599.91	67
M18J	I52.5R	32.65	Jehander	67.35	5823.70	62
M19R	I52.5R	36.11	Riksten	63.89	6347.59	61
M20B	I52.5R	35.14	Bro	64.86	6181.51	65
M21J	I52.5R	36.12	Jehander	63.88	6409.51	58
M22B	I42.5N	41.05	Bro	58.95	4202.11	66
M23J	I42.5N	42.10	Jehander	57.90	4358.33	61

It should be noted that the slump test and especially the slump flow test is geometry and density-dependent method. Size of the conical frustum used for measuring the flow is related to the fineness of mixture under study. Thus, the flow of mortars is measured by smaller cones such as mini-slump cone compared to the slump of concrete which is measured by Abrams' cone.

In order to compare the flow spread of mortars to concrete, the concept of the relative slump is conveniently used, as described earlier (see Eq. 8). The equation only considers the size of the bottom opening and dismisses effects of volume and height of the cone. Moreover, since a larger volume of material is used in Abrams' cone comparing to mini-slump cone, the higher mass of the sample facilitates the flow by a dynamic effect. Particles traveling from the top of the Abrams' cone will have a higher velocity and a

prolonged stoppage time comparing to mini-slump cone caused by the difference in their heights. Hence, for the same material, a larger relative slump should be expected for results obtained from Abrams' cone comparing to mini-slump cone.

In order to study the effect of frustum geometry on resulting relative slump, the Abrams' cone was cut in half of its height to make two new cones as shown in Fig. 4. Flow spread was measured by the new cones for some of the concrete mixes and compared to the relative slump of Abrams' cones.

The materials were poured inside the cones with no additional compaction force such as rodding or vibration to minimize the effect of compaction. Spread was measured by averaging perpendicular diameters of the stoppage shape.

Table 3 Concretes constituents and proportions

Mis ID	Cement		Fines		Ternary Mat.		Coarse	Water	W/C	Calc.SSA	Packing density %
	Type	Vol%	Type	Vol%	Type	Vol%	Vol%	Vol%	Kg/Kg	cm ² /cm ³	
C1A	II-42.5N	13	Riksten	34	—	—	34	20	0.52	1887.05	77
C1B	II-42.5N	13	Riksten	33	—	—	33	21	0.54	1887.05	77
C1C	II-42.5N	12	Riksten	32	—	—	32	23	0.64	1887.05	77
C2A	II-52.5N	14	Riksten	34	—	—	34	19	0.47	2227.21	75
C2B	II-52.5N	12	Riksten	32	—	—	32	25	0.68	2227.21	75
C2C	II-52.5N	12	Riksten	31	—	—	31	26	0.72	2227.21	75
C3A	II-52.5N	12	Jehander	33	—	—	33	22	0.60	2245.25	76
C3B	II-52.5N	12	Jehander	31	—	—	31	27	0.76	2245.25	76
C3C	II-52.5N	11	Jehander	30	—	—	30	28	0.83	2245.25	76
C4A	II-52.5N	15	Bro	32	—	—	32	20	0.42	2749	75
C4B	II-52.5N	15	Bro	32	—	—	32	22	0.46	2749	75
C4C	II-52.5N	14	Bro	29	—	—	29	27	0.61	2749	75
C5A	II-52.5N	14	Riksten	32	Limus 40	2	32	21	0.59	2755.41	75
C5B	II-52.5N	13	Riksten	30	Limus 40	2	30	26	0.73	2755.41	75
C6A	I-52.5R	12	Riksten	31	—	—	31	26	0.69	2816.33	74
C6B	I-52.5R	12	Riksten	31	—	—	31	26	0.72	2816.33	74
C6C	I-52.5R	12	Riksten	31	—	—	31	27	0.70	2816.33	74
C7A	II-52.5N	14	Jehander	17	Mid	19	19	31	0.76	2832	74
C7B	II-52.5N	14	Jehander	17	Mid	18	18	33	0.80	2832	74
C8A	I-52.5R	13	Jehander	34	—	—	34	20	0.50	2833.86	75
C8B	I-52.5R	12	Jehander	31	—	—	31	25	0.68	2833.86	75
C8C	I-52.5R	11	Jehander	30	—	—	30	29	0.83	2833.86	75
C8D	I-52.5R	11	Jehander	29	—	—	29	30	0.87	2833.86	75
C9A	I-52.5R	14	Bro	29	—	—	29	28	0.63	3486.20	74
C10A	I-52.5R	13	Jehander	17	Mid	19	18	33	0.78	3569.24	76
C10B	I-52.5R	13	Jehander	17	Mid	18	18	34	0.83	3569.24	76

Fig. 4 Conical frustums used for measuring the flow spread of mortars and concretes

5 Results and discussion

The flow of mixtures is commonly related to the water to cement ratio or water content of the blends. Figure 5 illustrates the dependency of the relative slump on w/c ratio of the examined cementitious mixtures. The parameter of the relative slump is chosen for comparison since mortars and concrete exhibit different flow spreads related to the size of the bottom opening of the cone used for conducting the measurement.

As can be seen in Fig. 5, different relative slumps can be achieved with the same w/c ratio. It should be mentioned that while the parameter of w/c provides some information about the water content of the mixtures, it does not define how the water is being consumed inside the mixture. Thus, in order to further investigate the effect of water content, it is essential to study water film thickness covering the particles in the matrix at the onset of flow as well as in flowing state as described in 5.1 and 5.2.

Water demand at the onset of flow is the minimum required water to put the mixture in a state where the addition of water will result in deformation of the mix and is equal to the water retaining capacity, β_w . Figure 6 presents a comparison between β_w for mortars and concretes while Table 4 reports β_w and E_w (i.e. water retaining capacity and deformation coefficient) for mixtures.

According to Fig. 6, the water retaining capacity increases with an increase in SSA for both mortar and concrete. While the trends are similar for mortar and concrete, the value of β_w is much smaller for the latter. As mentioned earlier, water retaining capacity is obtained from the sum of the volume of void filling

Fig. 5 Water to cement ratio versus relative slump measured by mini-slump and Abrams' cones

Fig. 6 Water retaining capacity of cementitious mixtures

water (W_{vo}) and the volume of water required to put the mixture at the onset of flow (W_{on}). The authors assume that the water film thickness at the onset of flow is related to specific surface area of particles, hence the same water film thickness is required for concretes and mortars with the same SSA. Mixtures can be produced with different SSA by altering volume share, particle size distribution, shape and fineness of constituents, likewise it is possible to achieve same SSA for mixtures with different proportions; however, fineness modulus of particles would be different.

The difference in the water retaining capacity of mortars and concretes with the same SSA is assumed to be related to the fact that the value of β_w , among other factors, is influenced by mixer efficiency see Eq. 10. Mixers with higher efficiency introduce more compaction energy to the mix resulting in particle matrix with higher packing density and hence lower voids to be filled with water. Various parameters affect the efficiency of mixers namely geometric volume of mixing container, feeding procedure, the arrangement of stirring blades, mixing velocity, power consumption, etc. [29, 30]. In the current study, the difference between water retaining capacities of mortars and concrete were related to the increase in packing density of particles in concrete due to higher compaction energy applied to the blend by the concrete mixer.

5.1 Relative water film thickness

The volume of relative excess water (W_{re}) is calculated by subtracting water retaining capacity from total

Table 4 Water retaining (β_w) and deformation coefficient (E_w) of mixtures

Mixture	β_w	E_w	Mixture	β_w	E_w
<i>Mortar mixtures</i>					
M1R	0.5552	0.03	M13R	0.5688	0.0445
M2B	0.5572	0.0441	M14B	0.6282	0.0348
M3J	0.6519	0.0544	M15J	0.7521	0.0519
M4R	0.5287	0.038	M16R	0.6274	0.037
M5B	0.5898	0.0415	M17B	0.6738	0.0469
M6J	0.667	0.0601	M18J	0.781	0.0491
M7R	0.5709	0.0338	M19R	0.6581	0.0503
M8B	0.6169	0.0377	M20B	0.7078	0.0476
M9J	0.6992	0.0335	M21J	0.8321	0.0414
M10R	0.6149	0.0311	M22B	0.6586	0.0563
M11B	0.664	0.0327	M23J	0.8062	0.032
M12J	0.7265	0.04			
<i>Concrete mixtures</i>					
C1	0.2519	0.02	C6	0.338	0.053
C2	0.2377	0.03	C8	0.2926	0.0384
C3	0.2868	0.0243	C10	0.3536	0.03
C4	0.28	0.0434			

water available in a unit volume of the mixture, according to Eq. 4. The thickness of relative water is calculated based on Eq. 7 and is shown for both mortars and concrete in Fig. 7 in addition to the standard deviation error bars for a series of mortar and concrete tests.

The negative values of WFT in Fig. 7 indicate a lack of water for surrounding the particles which lead to mixtures with zero slumps.

It should be mentioned that due to differences in geometry of mini-slump cone (used for measuring the flow of mortars) comparing to Abrams' cone (used for

measuring the flow of concrete), a larger relative slump should be expected in Abrams' cone comparing to mini-slump cone for the same mixture.

Nevertheless, Fig. 7 shows that relation between relative water film thickness and the relative slump is valid for both mortars and concrete, meaning that the relative water film thickness is dependent chiefly on SSA of mixtures since concrete and mortars with similar SSA require similar WFT_{re} , although the fineness modulus of the blends are different, see Fig. 8. Concrete mixtures showed regression of 84% for the relation between the relative slump and WFT_{re} .

Fig. 7 Relative water film thickness versus relative slump for cementitious mixtures **Fig. 8** Dependency of relative water film thickness on SSA of cementitious mixtures

Figure 8 confirms that the relation between relative WFT and SSA is valid for mortar and concrete alike. However, the value of relative WFT_{re} is not enough for estimating flow spread of mixtures. The relation between WFT_{on} at the onset of flow and SSA are also required for predicting water demand of blends.

5.2 Water film thickness at the onset of flow

The amount of water required for putting a mixture at the onset of flow is calculated by subtracting void filling water from the water retaining capacity according to Eq. 5. The value is influenced by packing density since higher packing density leads to a reduction in void filling water and hence more water will be available to the mixture as excess water. The packing density of particles in mixtures, in turn, is affected by the efficiency of mixers. Wallevik and Wallevik [31] showed that the same recipes of self-compacting concrete made with different mixers resulted in different consistencies. According to [32], increasing the intensity of mixing results in a decrease in yield stress and water demand of mixtures, the plastic viscosity, on the other hand, is less affected by mixing efficiency.

Using mixers with higher efficiency leads to an increase in packing density and decrease in void filling water. This means that for the same β_w , available excess water increases with an increase in packing density. Since a mixture produced in Hobart mixer was under less compaction energy comparing to concrete mixers, the packing density of the solid skeleton is lower than the one made in a concrete mixture and as a result more water is required for filling the voids in the blend made with a Hobart mixer comparing to a more efficient mixer. The packing density of particle plays a major role in the calculation of WFT_{on} at the onset of flow. The water film thickness at the onset of flow is plotted against S in Fig. 9, assuming mortar and concrete experience no compaction energy (packing density in the loose state).

Since relative water film thickness showed to be the same for materials with the same SSA regardless their fineness modulus (see Fig. 7), it is here assumed that the same concept is valid for WFT_{on} at the onset of flow. In that sense, the variation between WFT_{on} for mortars and concretes is blamed on compaction energy of mixers. Thus, the effect of compaction can be calculated for different mixers by averaging the

Fig. 9 Water film thickness at the onset of flow for cementitious mixtures

increase in packing density required to arrive at the same WFT_{on} for same SSA in both mortars and concrete. Corrected WFT_{on} for the mixer used in this study is shown in Fig. 10 where it can be seen that the available water film thickness increases inside the concrete once the void fraction is reduced by a correction factor. Correlation between Figs. 10 and 11 suggest that by reducing void fraction according to Eq. 10 so the WFT_{on} of mortar and concrete fall in the same range for the mixers used in this study.

$$e_{\text{mixer}} = k_{\text{mixer}}(1 - \phi_{\text{loose}}) \quad (10)$$

where e_{mixer} is the void ratio of materials in the mixture, the value of k_{mixer} is influenced by the efficiency of mixers and mixing time and can be interpreted as an indication of compaction energy introduced to the blend by the mixer.

Fig. 10 Corrected water film thickness at onset of flow for cementitious mixtures

Fig. 11 Effect of cone geometry on the relative slump of concrete

The magnitude of the mixing efficiency coefficient, k_{mixer} , varies between 0 and 1 where a lower value indicates higher mixer efficiency and consequently larger compaction energy, in this paper value of 0.33 used as the k_{mixer} for the ZH 75 HE Zyklus rotating pan mixer utilized for mixing the concrete. It should be mentioned that different materials do not act the same way under compaction and the extent of the effect is related to shape and particle size distribution of particle among other factors. The constant in Eq. 10 is close to what was found by Hunger [33] as the average ratio between void fraction in the loose and compacted state:

$$e_{\text{comp}} = 0.428(1 - \phi_{\text{loose}}) \quad (11)$$

Moreover, Kwan and McKinley [28] in a study on packing density of limestone fines concluded that packing density increases substantially in the presence of water, with no compaction and superplasticizer added. Packing density in the wet state showed to lower porosity of materials by around 30% comparing to loose packing:

$$e_{\text{wet}} = 0.73(1 - \phi_{\text{loose}}) \quad (12)$$

The correlation coefficient, k_{mixer} , in this case, is smaller than both mentioned values meaning that the blend inside the mixer had a more substantial reduction in void fraction comparing to both compacted packing and wet state. It should be emphasized again that the correlation coefficient is related to the type of mixer that is used for the production of cementitious mixes and requires calibration for different mixers.

Generally, lower compaction energy for mixing leads to higher yield stress [34]. Research by [35] showed that the plastic viscosity of mixtures decreases with an increase in shear rate and rotational speed of the mixer. The study compared viscosity of different paste mixed with variety of mixers including hand mixing, Hobart mixer, and Ross mixers on two different speeds and it was concluded that increasing the shear rate of mixers results in improved flow properties. Nevertheless, the value of k_{mixer} in Eq. 10 was assumed to be equal to one for Hobart mixers as the reference since the water film thickness that the study is based on were measured on mortar mixtures that were made using a Hobart mixer.

5.3 Effect of cone geometry on flow

Translating the flow measured with mini-slump cone to Abrams' cone is problematic and imposes an assumption about the sample shape at the stoppage which is related to the surface tension of the mixtures [36]. The effect of geometry of cones was experimentally studied by measuring the flow of some of the concrete mixtures in two cones made by dividing an Abrams' cone in half of its height, see Fig. 4. Relative slumps of spreads were calculated for each cone and are presented in Fig. 11. Due to the small ratio between the opening of mini-slump cone and the maximum diameter of aggregates in concrete, results from tests with mini-slump cone would be influenced by container wall effect, thus is invalid and as such not measured.

Figure 11 confirms the fact that for the same material larger relative slump should be expected when the size of the bottom opening of cone increases, which is more evident for oversaturated mixtures with a larger flow spread. By that logic, the relative slump of mini-slump cone should be smaller than the relative slump of the studied cones. According to Fig. 11, water content required for flow is related to the size of cone used for measuring the spread. This allows explaining the difference between slump of the mini cone to Abram's cone at the onset of flow where a mixture with zero-slump measured in mini-slump cone, shows some degree of flowability once measured by Abrams' cone.

Aside from the geometry of the slump cones, the difference in density of mortar and concrete, depending on the recipes, introduces another source of error

for comparing the flow of mortars to concrete. Moreover, mortars and concrete do not have the same air content. It was found that increasing air content in concrete mixtures increases flowability [37]. This can be explained by means of excess water layer theory. An increase in air content can be translated to the increase in total packing of materials since the air bubbles are inaccessible for water, similar to solid particles. Augmentation of packing density means there will be less water needed for filling the voids (W_{vo}) hence more water will be available as excess relative water (W_{re}).

6 Conclusion

Previous studies revealed that flow behavior of cementitious mixtures is strongly correlated to specific surface area, water demand and packing density of the blends [3–5, 16]. The overall effects of the mentioned parameters are reflected in WFT enveloping the solid particles. Current article investigates the influence of WFT on the flow of mortars and concrete. Moreover, the relation between spread flow of mortars measured by mini-slump cone and spread of concretes obtained from Abrams' cone is studied in an attempt to relate concrete mix design to characteristics of its mortar. Generally, tests on mortars are preferred over tests on concrete as a quick way to estimate the flow behavior of mixtures. Tests on mortars require a smaller volume of sample and less time and include less complexity comparing to concrete tests.

Based on presented results following conclusions can be drawn:

- Excess water layer theory and concept of WFT proved to be a practical approach for studying the flow of granular mixtures. The correlation between relative WFT and flow is valid for both concrete and mortar in a wide range of mixtures with various proportioning, cement type, water to cement ratio and SSA. The study confirms that although rheological behavior of cementitious mixtures depends on many parameters in an inter-related complicated manner, the flow is indeed chiefly reliant on WFT verifying the hypotheses put forward in the study.
- Mortars showed to have much higher water demand than concrete. Since WFT is assumed to

be only dependent on SSA, mortar and concrete with the same SSA and water content are expected to have a similar flow. In reality, the concrete would be more flowable due to compaction energy introduced to the blend by mixer since concrete mixers have higher efficiency comparing to mixers used for mortars.

- Compaction energy of mixer proved to have a significant effect on the flowability of mixtures. Higher compaction energy leads to higher packing density and consequently less demand for void filling water. In the current study, the parameter is quantified by comparing water film thickness at the onset of flow for mortar and concrete with similar SSA.
- A comparison between flow spread measured with conical frustums of different sizes indicates that for the same concrete mixture, larger relative slump should be expected for molds with higher volume and larger bottom opening.
- The concept of water film thickness can be used for estimating the flowability of concrete mixtures and producing recipes for preliminary proportioning of the blends based on flow properties of their mortars.
- The concept of excess water layer theory and WFT can be used for proportion constituents of mixtures by considering the combined effect of packing density and SSA. The performance of fresh concrete cannot be based on packing density approach alone as concretes produced at maximum packing density tend to be “harsh” and resistant to shear deformation.

It should be noted that no superplasticizer was used in producing concrete mixtures with the purpose of isolating the effect of WFT; however, modern concretes are rarely made without superplasticizer. A downside of excluding superplasticizer from the mixtures is the possibility of formation of flocculation especially in blends with finer particles and higher SSA. At the same time, the packing density slightly increases due to the collapse of flocculating structures by the increase of superplasticizer [10, 28]. Although it is possible to measure the WFT in the presence of superplasticizer, the results would be valid only for that type of admixture and for special dosages. Nevertheless, the current article assumes that the no flocculation exist in the mixtures and the water film is

homogenously dispersed among the particles, a simplification commonly used in similar studies [33, 38]. The assumption can be justified according to the literature where [6] concluded that the flow spread of blends increases linearly with water to binder ratio at the rate that appears to be independent of the superplasticizer dosage, except for very low dosage of the admixture. Similar trends were observed by [10] where the increase of superplasticizer dosage decreases the water demand of mixtures linearly. This suggests that the superplasticizer, at least passed the minimum dosage, have a neglectable effect on the deformation coefficient of the mixtures. Hence, the phenomenon can be used for incorporating the effect of superplasticizer and the dosage on the WFT at the onset of flow of the mixtures by modifying the curve shown in Fig. 10 as future work.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Informed consent was obtained from all individual participants included in the study.

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