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The Influence of the Fines on the Early-Age Behavior of Zero-Slump Concrete

Abstract

This paper presents experimental investigations on the early-age behavior of zero-slump concrete. In this context, compaction behavior and green-strength are used to characterize the early-age behavior of zero-slump concrete.
First, the influence of the granulometric properties of the fines is discussed in detail. For this purpose, the early-age behavior of two different fines (quartz flour and fly ash) is investigated by means of the intensive compaction test (IC-test). The tests on the influence of the fines focus on effects caused by differences in the particle shape and the use of a plasticizing admixture. The conducted tests on the compaction behavior of the fines and their corresponding green-strength are extended to continuously graded granular mixes. Here, the influence of optimized particle packing on the early-age behavior is presented and a comparison based on the aforementioned quartz flour and fly ash is made.

1 Introduction

Zero-slump concrete, also known as no-slump concrete or earth-moist concrete, is used for the production of concrete mass products, such as sewage pipes, concrete slabs, paving blocks, masonry blocks, roofing tiles, and curbstones. The early-age behavior of this type of concrete is characterized by its low water content and its stiff consistency, which corresponds to a slump of 6 mm or less [1]. Therefore, the characteristics of zero-slump concrete allow for direct stripping of the unhardened product after filling and vibrating the mold and subsequent transport to a place with defined curing conditions [2]. This phenomenon of the fresh concrete is referred to as green-strength and allows for short processing times and enables an efficient use of molds and production machines. In this respect, the term green-strength is defined by Bornemann [3] as strength of the unhardened product to keep its original shape until the cement starts to set and the hydration products provide sufficient strength.
The green-strength of the fresh concrete can be explained by means of soil mechanical models that are also used for the description of cohesive soils [3]. However, it has to be mentioned at this point that the cohesive character of zero-slump concrete is differing from the 'real cohesion' that can be found in cohesive soils like clay. According to [4], this 'real cohesion' is only obtained by soils that adhere after wetting and subsequent drying and where significant forces are required to breake up the hardened structure of the dry material. Although this mechanism cannot be adapted to zero-slump concrete completely, the Mohr-Coulomb failure criterion, as depicted in Figure 1, allows for explaining the green-strength of zero-slump concrete. In this context, the green-strength of zero-slump concrete is governed by the apparent cohesion that is expressed by the 'real cohesion' (intersection point of the tangent in Figure 1) of cohesive soils and the

‘internal friction’ of the material that is represented by the inclination of the tangent in Figure 1.
The cohesive character of zero-slump concrete in its fresh state is caused by the formation of capillary forces. Capillary forces are formed at the contact points of the fine particles as a result of the partly saturated void fraction of the granular skeleton. This partial saturation of the void fraction causes the formation of liquid bridges between the smaller particles at their contact points. An attractive force is formed in the liquid bridge that is depending on the diameter *D* of the involved particles, the surface tension γ of the wetting liquid, the resulting contact angle between the surface of the liquid and the particle surface, and the distance between the involved particles.

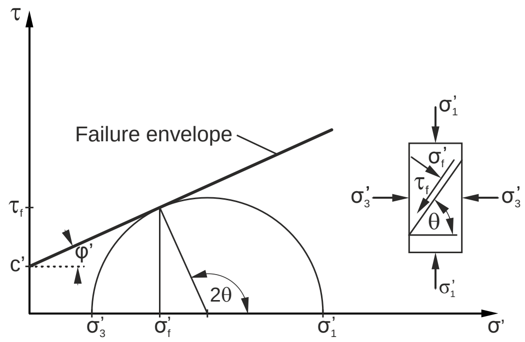

Figure 1: Stress conditions of the Mohr-Coulomb failure criterion [4].

As outlined before, the early-age behavior of zero-slump concrete is important for the production of concrete mass products and is governed by a number of different parameters. In this case, both compaction behavior and green-strength of the fresh concrete are influenced by the granulometric properties of the fines (particle size and particle shape), the content of fines, the water content, and the surface tension of the wetting liquid. By means of the present study, the intensive compaction test (IC-test) will be used to investigate the influence of the aforementioned parameters on the compaction behavior and the green-strength of zero-slump concrete and conclusions to the apparent cohesion and internal friction will be made.

2 Experimental Program

2.1 Materials

As outlined before, the compaction behavior and the green strength of zero-slump concrete are governed by the granulometric properties of the fines and the resulting water demand. Hence, two different fines have been selected in order to investigate their influence on the early-age behavior. The selected fines are quartz flour and fly ash with similar particle size distribution (PSD). The PSDs of the selected fines are depicted in Figure 2a. The quartz flour was chosen, as it is an inert fine material that does not react with water, but having similar granulometric properties as cement (PSD and angular particle shape). That way, the influence of the proceeding hydration on the early-age behavior is prevented. The selected fly ash is characterized by a similar PSD as determined for the quartz flour, but having more spherical particles. Furthermore, the selected fly ash is also considered to be inert when mixed with water. Besides the influence of the granulometric properties of the fines, the effect of chemical admixtures on the early-age behavior was investigated. A polycarboxylate-based superplasticizer (SP1) was selected for that purpose and applied in combination with the selected fines. Figure 2b illustrates the influence of the selected SP on the surface tension of the wetting liquid. The measurements of the surface tension have been performed on a Krüss K11 tensiometer using the plate method.

For the design of continuously graded granular mixes, river sand 0-2 and river gravel 2-8 were selected. Both aggregate fractions consist primarily of quartz and were dredged from areas along the Lower Rhine. The PSDs of the sand 0-2 and the gravel 2-8 are depicted in Figure 2a.

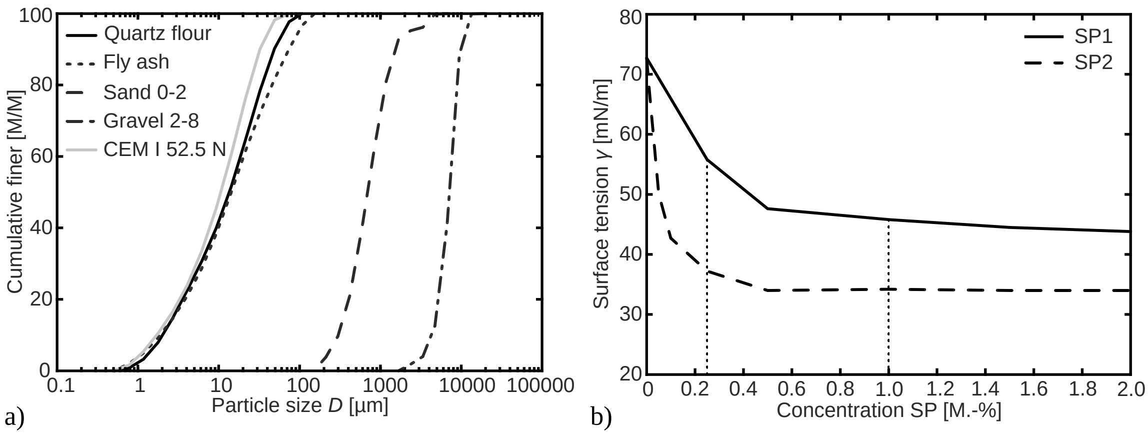

Figure 2: Material characteristics: a) PSD of the selected materials; b) Influence of two different superplasticizers on the surface tension of water and applied concentrations of SP1. The measurements have been performed on a Krüss K11 tensiometer using the plate method.

2.2 *Mix Designs*

The experimental investigations that were carried out in the first instance on the selected fines (quartz flour and fly ash) were extended to continuously graded mixes having a maximum particle size of 8 mm. The continuously graded mixes were designed using the optimization algorithm introduced by [7]. This optimization algorithm uses the modified Andreasen and Andersen equation suggested by [8] and which follows from:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \quad (1)$$

with $P(D)$ as cumulative finer volume fraction of the particle size D, D_{max} and D_{min} giving the maximum and minimum particle size of the mix, respectively, and q determining the distribution modulus of the grading curve. By means of this algorithm, continuously graded granular mixes, which are composed of varying raw materials, can be designed that follow a given grading curve, expressed by Eq. (1), with lowest deviation.

Two different distribution moduli of $q = 0.25$ and $q = 0.40$ were used to compose granular mixes with a high ($q = 0.25$) and low ($q = 0.40$) content of fines, respectively. The selected quartz flour as well as the fly ash were used as fines in the designed granular mixes (Q1, Q2, F1, F2) in order to ensure comparable conditions and to relate the fundamental properties of the fines to the results obtained on continuously graded granular mixes. The mixes were designed in that way that comparable conditions regarding the content of fines for equal distribution moduli q were achieved. The mix designs that are presented in Table 1 are based on a water content Ψ_m of about 3.0 M.-% till 3.25 M.-%. The corresponding PSDs of the designed mixes are depicted in Figure 3.

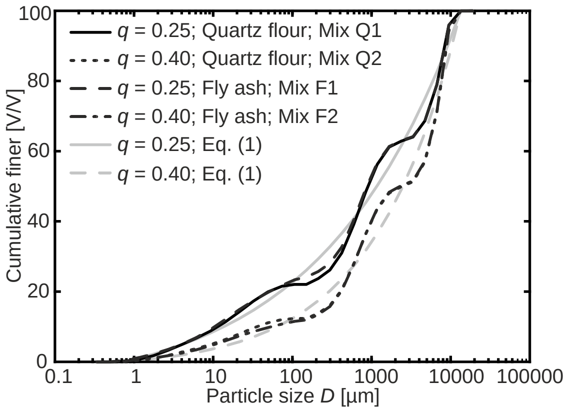

Figure 3: PSD of the designed granular mixes used for the experimental investigations on the early-age behavior; D_{max} = 11.2 mm, D_{min} = 0.63 µm.

Table 1: Mix proportioning and characteristics of the designed mixes.

	Mix composition [kg/m³]			
Material	**Q1**	**Q2**	**F1**	**F2**
Quartz flour	520.5	290.4	-	-
Fly ash	-	-	477.6	237.2
Sand 0-2	995.3	909.5	949.5	933.7
Gravel 2-8	844.3	1160.6	846.5	1164.3
Water	79.4	79.2	76.3	71.0
Mix characteristics				
Distribution modulus q	0.25	0.40	0.25	0.40
w/p ratio	0.15	0.27	0.16	0.30
Ψ_m	3.25	3.25	3.25	3.0
Fines [kg/m^3]	520.5	290.4	477.6	237.2
Paste [l/m^3]	275.8	188.8	292.3	178.3

2.3 Compaction Behavior

The selected fines as well as the designed mixes were mixed with water and tested for their compaction behavior to study the influence of varying water content. The compaction behavior was tested using the IC-test as this test provides an accurate and convenient method to evaluate the workability of granular mixes with respect to their compaction behavior. Consequently, the IC-test was also used by other researchers, such as Juvas [9] as well as Käppi and Nordenswan [10].

The method and the equipment of the IC-test were developed by I. Paakkinen in 1984 in Finland [5] and were later adopted by the Nordtest method [11]. The sample is compacted by a combination of pressure and shear movement without the use of additional vibration energy. This principle is referred to as shear-compaction. A detailed description of the working principle is given in [5] as well as [6]. The applied pressure, rotation speed, as well as the inclination of the sample to the vertical axis of the device can be adjusted and were kept constant during each test.

In order to obtain constant test condition, the following parameters have been used to produce samples with a diameter of 100 mm and a height of about 100 mm:

- Cylinder inclination (α_{ICT}): 40 mrad
- Compaction pressure: 250 kPa
- Working speed: 60 rpm
- Duration (N): 100 cycles.

Possible variations in the height of the sample caused by improved compaction behavior and higher packing fractions were compensated by an increased sample mass so that a constant height of about 100 mm was obtained for all samples.

2.4 Green-Strength

The samples that have been produced by the IC-tester were stripped from the sample holder directly after the test was finished and subsequently tested for their green-strength in the fresh state. Stress-strain relations using a uniaxial compressive strength test were used to evaluate the green-strength in this research. Therefore, the fresh samples have been subjected to compressive stresses. The uniaxial compressive strength test was performed on a Zwick Z020 testing machine. All samples were tested displacement-controlled with a crosshead speed of 1 mm/min until the sample failed and the resulting force and axial deformation were recorded.

3 Results and Discussion

3.1 Compaction Behavior

Fines

The influence of the selected fines on the compaction behavior was investigated using the IC-test. The obtained results for varying water content are depicted in Figure 4 for pastes made with quartz flour and fly-ash.

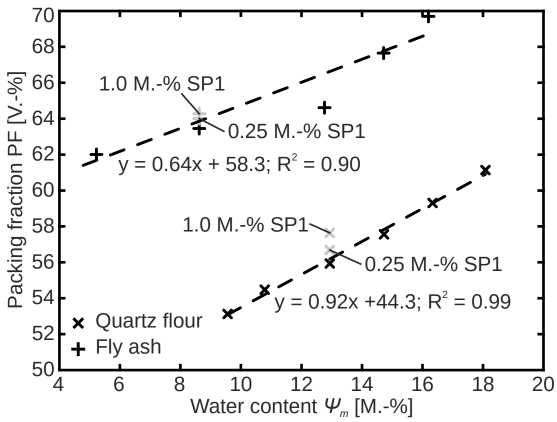

Figure 4: Packing fractions of pastes made with quartz flour and fly-ash for varying water contents Ψ_m (mass-based). The shaded values represent comparable measurements with a SP content of 0.25 M.-% and 1.0 M.-%, respectively.

It is evident from the data illustrated in Figure 4 that the compaction behavior of both fines differs to a large extent. The fly ash results in higher packing fraction for comparable water content than the quartz flour and less water is needed to obtain the so-called ‘slurry point’ that is characterized by a complete saturation of the void fraction. This fact can be related to the difference in the particle shape of the applied fines. The selected fly ash is mainly composed of spherical particles compared to the more angular particles of the quartz flour. Hunger [12] reports a shape factor ξ of 1.09 for the applied fly ash, whereas a value of about 1.4 has to be considered for the quartz flour. The shape factor ξ expresses the ratio of the effective surface area of a particle to the surface area of an ideal sphere with equal volume [12]. According to this definition, a lower value of

ξ corresponds to a more spherical particle shape, and results in a value of 1.0 for spheres.

The more spherical shape of the fly ash and the resulting ball-bearing effect show a beneficial influence on the compaction behavior and the final packing fraction that was obtained (cp. Figure 4). In contrast to this, the angular shape of the quartz flour increases the internal friction of the mix and lower values of the packing fraction were obtained for comparable compaction efforts and water content.

Chemical admixtures

Besides the effect of the granulometric properties of the fines, the influence of chemical admixtures on the early-age behavior was investigated. For this purpose, the compaction behavior and the green-strength of the fines were determined for fixed water content, but varying SP concentration (SP1). The water content was fixed to be 12.9 M.-% for the quartz flour and 8.2 M.-% for the fly ash. The investigated SP concentration of the mixing water amounts to 0.25 M.-% and 1.0 M.-%, respectively (cp. Figure 2b). The compaction behavior of the samples was investigated by means of the IC-test in two different ways. In the first instance, the sample was compacted to the same packing fraction as obtained by the tests without SP and the required working cycles as well as the green-strength were determined. Next, the sample was compacted using the same compaction efforts as applied for the tests without SP (100 working cycles) and the influence on the compaction behavior and the green-strength was determined. The shaded values depicted in Figure 4 show the packing fractions that were obtained for different SP concentrations (SP1). Detailed values of the conducted tests are given in Table 2.

Table 2: Test results of the IC-test for different SP concentrations and compaction regimes.

	Quartz flour			**Fly ash**		
	No SP	**0.25% SP1**	**1.0% SP1**	**No SP**	**0.25% SP1**	**1.0% SP1**
Working cycles#	100	71	41	100	83	62
Packing fraction† [V.-%]	55.9	56.7	57.6	63.5	64.0	64.3
Green-strength# σ_{gre} [N/mm²]	0.127	0.102	0.095	0.080	0.062	0.066
Green-strength† σ_{gre} [N/mm²]	0.127	0.119	0.125	0.080	0.076	0.075

Determined for equal packing fraction as obtained without SP addition.
† Determined after 100 working cycles.

The test results demonstrate that the compaction behavior is improved when a plasticizing admixture is used and that this effect is depending on the SP concentration. In both cases, quartz flour and fly ash, less working cycles were required to obtain equal packing fractions as determined for the tests without SP. The same holds for the packing fractions that were obtained for equal compaction efforts. Here, the packing fractions after 100 working cycles increased with increasing SP content.

Grading

The experimental investigations on the influence of the fines on the compaction behavior were extended to continuously graded mixes. For that purpose, the four different mixes with varying distribution moduli *q* as listed in Table 1 were used and the corresponding results of the IC-test are depicted in Figure 5.

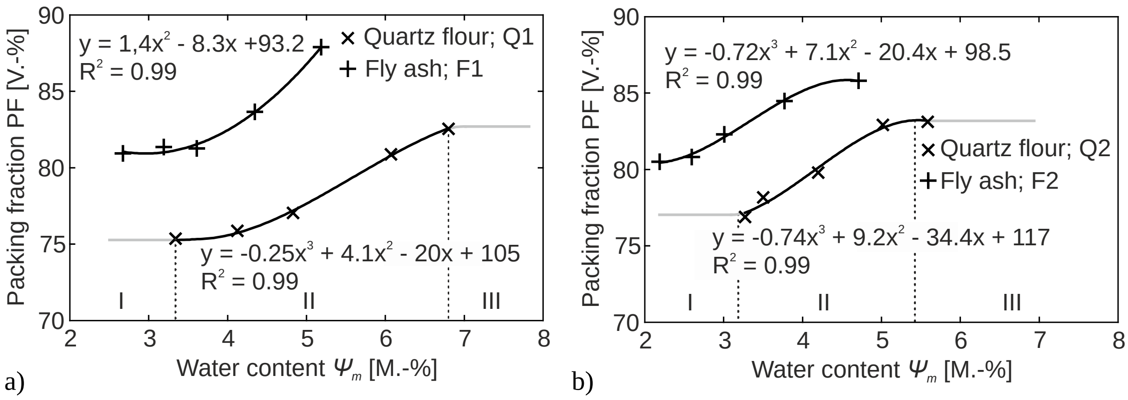

Figure 5: Packing fraction of the tested mixes for varying water content Ψ_m (mass-based) and suggested compaction regimes (I – dry state, II – moist state, III – wet state): a) q = 0.25; and b) q = 0.40.

The assumption of the beneficial effect of spherical particles on the compaction behavior is also confirmed by the tests on continuously graded granular mixes (see Figure 5). This fact was already demonstrated by the experimental investigations carried out on the fines only and applies for both investigated distribution moduli of $q = 0.25$ and $q = 0.40$, respectively. Furthermore, the experimental data reveal that a lower distribution modulus q results in better compaction behavior and higher packing fraction. This effect is more evident for the applied fly ash than for the quartz flour. Here, the higher content of spherical particles increased the packing fraction of the fly ash mixes to a remarkable extent. The maximum packing fraction of the tested fly ash mixes increased from 85.8% to 87.9% when a distribution modulus of $q = 0.25$ was used instead of $q = 0.40$. Furthermore, an insight into the sensitivity of the designed mixes on changes in their water content is provided by the data depicted in Figure 5a and Figure 5b and will be discussed in the following using the designed quartz flour mixes as example.

As illustrated in Figure 5a, the graph obtained by the IC-test for varying water content of the quartz flour mix Q1 differs from the compaction curve of the classical Proctor test as explained by Bornemann [3] and Craig [4]. The Proctor test gives a value for the optimum water content at which highest dry density of the sample is obtained. This point of optimum water content for highest packing fraction was not obtained by the IC-test. Here, the compaction behavior can be divided into three regimes as illustrated in Figure 5a and which are:

Dry state: This state is represented by the shaded horizontal line in sector I of Figure 5a. Variations in the water content of the mix show no or only minor effects on the obtained packing fraction. The water content of the mix is too low to form water layers around the particles that have a lubricating effect and that improve the compaction behavior. Therefore, the packing fraction in this state is equal to the dry condition or only slightly higher.

Moist state: This state is illustrated by the black solid line in sector II of Figure 5a. The lubricating effect of the particles grows in this state and the packing fraction increases with increasing water content. This state determines the optimum range for the practical application of zero-slump concrete in production.

Wet state: This state is indicated by the shaded horizontal line in sector III of Figure 5a and is determined by the so-called 'slurry point' of the sample. In this state, a further increase of the water content is not resulting in higher packing fraction as the granular mix obtained the highest possible densification and minimum void fraction. A further increase in the water content shows no positive effect on the packing fraction and excessive water drains only from the compacted sample as the remaining void fraction is saturated with water. At this point, the degree of saturation S_w of the void fraction is larger than 90%.

The range of the moist state (sector II) determines the aforementioned sensitivity of the designed mix on changes in the water content. The width of sector II is depending on the content of fines and increases with decreasing distribution modulus *q* (cp. Figure 5). Consequently, mixes with a lower distribution modulus *q* are less sensitive to small changes in their water content due to their higher amount of fines and their compaction behavior is less affected.

3.2 Green-Strength

Fines

Information on the deformation behavior and the green-strength of the selected fines can be derived from the stress-strain graphs depicted in Figure 6. Although the more spherical shape of the fly ash and the resulting ball-bearing effect influenced the compaction behavior and the final packing fraction in a positive way, the green-strength of the tested fly ash samples was influenced negatively. Here, higher green-strength was measured for the quartz flour samples than for the fly ash ones. This fact demonstrates that the internal friction of the mix has a larger influence on the green-strength than the packing fraction or the water content of the mix. The maximum green-strength that was obtained near the slurry point amounts to 0.173 N/mm² for the quartz flour having a water content of 18.2 M.-%. The corresponding value of the tested fly ash amounts to 0.161 N/mm² for a water content of 16.2 M.-%.

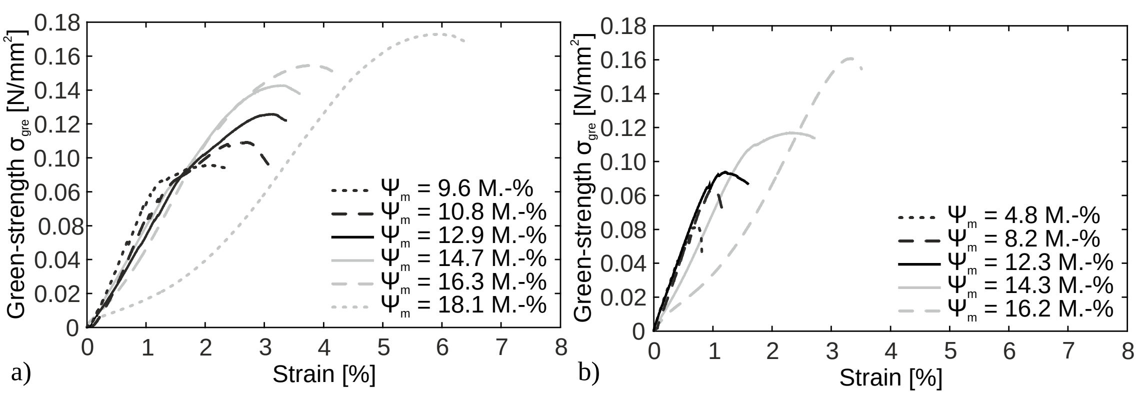

Figure 6: Stress-strain curves of the tested fines for varying water contents Ψ_m (mass-based): a) quartz flour; and b) fly ash.

Moreover, information on the deformation behavior of the tested samples can be derived from the graphs depicted in Figure 6. The higher internal friction of the quartz flour samples results not only in higher green-strength, but has also an effect on the deformation behavior near the maximum load. In this range, larger plastic deformations were measured for the quartz flour than for the tested fly ash. The fly ash samples showed a rapid decrease in their green-strength when the maximum load was reached and which was not observed for the quartz flour. This confirms that the grain interlocking is an important aspect for the green-strength of fresh concrete and the deformation resistance of the concrete in its early-age.

A further interesting fact was observed for the deformation behavior of the samples near the so-called slurry point. At this point, the remaining void fraction of the samples is almost saturated with water and the degree of saturation amounts to values larger than 90%. According to the definitions given by Halsey and Levine [13] as well as Rumpf [14], the capillary forces should decrease at this point as liquid bridges do not exist anymore or reach at least a constant value. Consequently, the green-strength of the samples should also decrease near the slurry point. However, this was not the case as highest green-strength was measured at this point and indicates, again, that the internal friction, caused by the particle shape and high packing fraction, dominates the green-strength.

Chemical Admixtures

It was demonstrated by the aforementioned measurements that the applied SP improved the compaction behavior of the tested fines. The application of a plasticizing admixture is not only influencing the compaction behavior, but shows also an effect on the green-strength as illustrated in Figure 7.

The green-strength of the tested samples that were compacted to the same packing fractions as obtained without SP addition decreased with increasing SP content. This fact demonstrates that the green-strength is also affected by the surface tension of the wetting liquid and that with increasing SP content the surface tension decreases. According to Rumpf [14], a lower surface tension γ results in lower adhesive forces between the fine particles and decreases, therefore, the green-strength (cp. Figure 2b, as well as Figure 7).

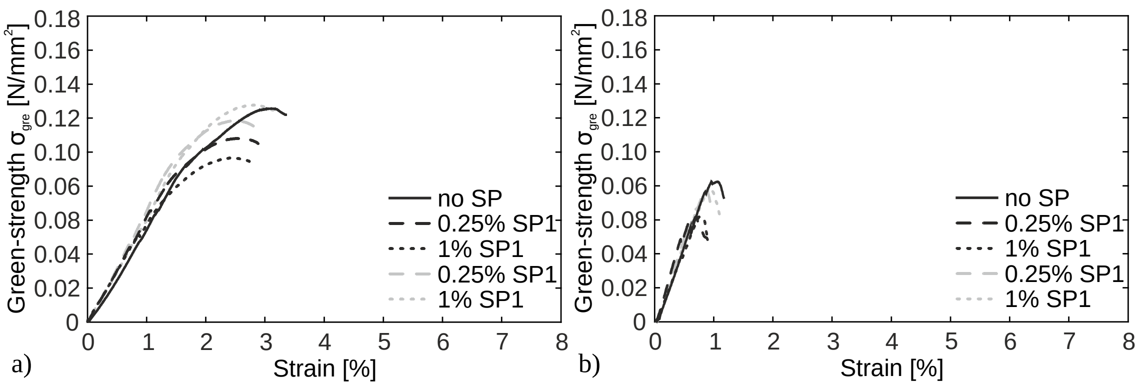

Figure 7: Stress-strain curves for constant water content Ψ_m (mass-based) and varying SP content: a) quartz flour, Ψ_m = 12.9 M.-%; and b) fly ash, Ψ_m = 8.2 M.-%. The shaded graphs show the stress-strain curves that were obtained after 100 working cycles with similar SP content.

This negative effect, caused by the lower surface tension of the wetting liquid, is compensated when equal compaction efforts are applied. In this case, the packing fraction after 100 working cycles increases and similar values of the green-strength are obtained as illustrated by the shaded graphs in Figure 7.

Grading

Variations on the granulometric properties of the designed mixes, such as fines content and particle shape of the fines, have not only an impact on the compaction behavior, but influence also the green-strength of the fresh mix. As illustrated by the data depicted in Figure 8, the green-strength of the mixes containing quartz flour was decreasing with increasing distribution modulus *q* and decreasing fines content. Similar observations are reported by Bornemann [3], which are explained by the higher cohesive character of mixes with high paste content. Furthermore, the higher fines content improves the compaction behavior of the mix and more contact points of particles in the micro range exist. Similar observations were made for the mixes containing fly ash that are depicted in Figure 9 and an optimized zero-slump concrete mix described in [6].

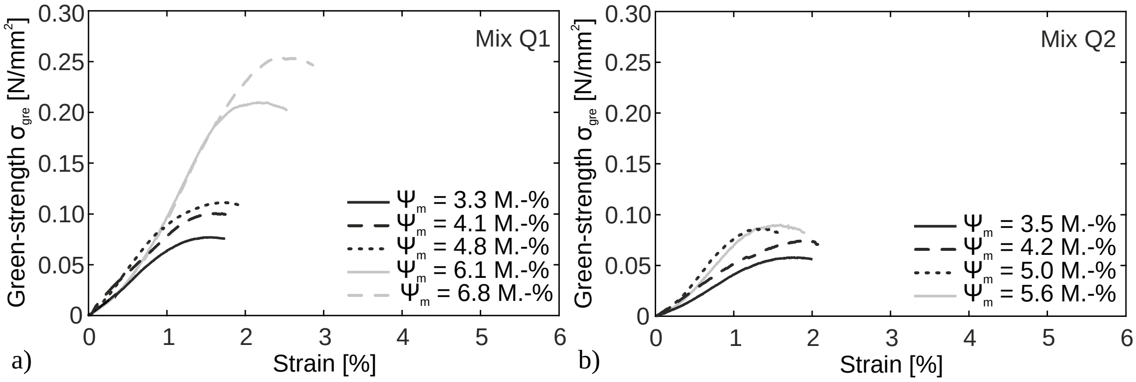

Figure 8: Stress-strain curves for varying water content Ψ_m (mass-based) of the designed granular mixes containing quartz flour: a) Mix Q1, $q = 0.25$; b) Mix Q2; $q = 0.40$;

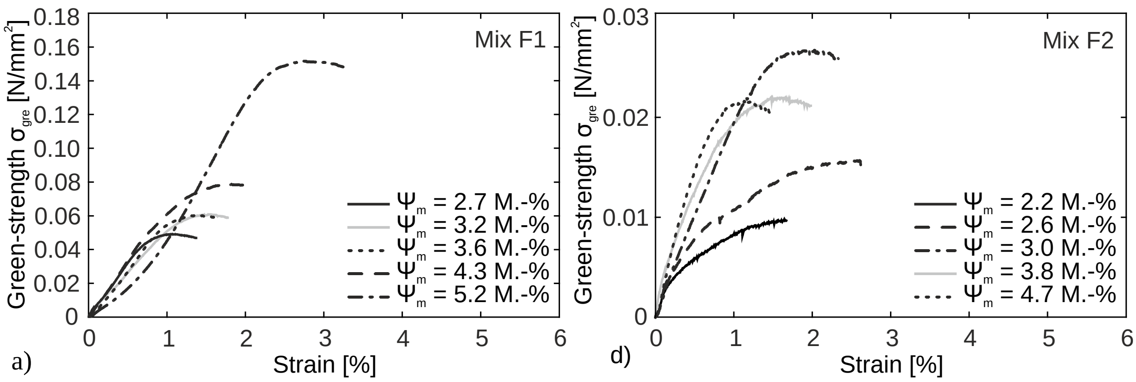

Figure 9 Stress-strain curves for varying water content Ψ_m (mass-based) of the designed granular mixes containing fly ash: a) Mix F1, $q = 0.25$; b) Mix F2, $q = 0.40$.

Although the spherical shape of the fly ash improved the compaction behavior and was resulting in higher packing fractions (see Figure 5), the green-strength of these samples is lower than that of samples containing quartz flour. This fact is related to the lower internal friction of the mixes containing fly ash. In this respect, the packing fraction of mixes that contain spherical particles was higher than for similar mixes with angular particles and is mainly caused by the ball-bearing effect and the lower grain interlocking of the spherical particles, which also resulted in lower green-strength values.

3.3 Discussion

Different factors that influence the early-age behavior of zero-slump concrete were investigated and have been discussed in this paper. The experimental results reveal that the compaction behavior and the green-strength of zero-slump concrete are affected to a large extent by the granulometric properties and the shape of the fines. In view of the compaction behavior, spherical particles increase the packing fraction of zero-slump concrete mixes, but reduce their green-strength as the internal friction of the mix is reduced due to less grain interlocking. In this respect, angular particles, such as the applied quartz flour, show a beneficial effect on the green-strength, but lower packing fractions are obtained. Furthermore, it was demonstrated that the internal friction of the granular mix has a larger impact on the green-strength than the formation of capillary forces that are formed in the liquid bridges between the fines. The internal friction of the mix depends on the particle shape of the fines and the obtained packing fraction, which is depending on the water content of the mix. However, higher green-strength was obtained for mixes of angular particles although their packing fraction was lower than that of mixes with spherical particles.

The application of a plasticizing admixture improved the compaction behavior, but reduced also the green-strength for similar packing fraction. This negative effect of plasticizing admixtures on the green-strength is related to their influence on the surface tension of the wetting liquid. As illustrated in Figure 2b, the surface tension of the wetting liquid decreases with increasing SP content and results in lower adhesive forces between the fines. This decrease in the green-strength was compensated when the sample was compacted with the same compaction effort as applied to the same mix without the use of a plasticizing admixture. In this case, the application of the plasticizing admixture increased the final packing fraction, which was resulting in higher internal friction of the sample and comparable green-strength as obtained for the same samples without a plasticizing admixture.

The compaction behavior and the green-strength of continuously graded mixes following the modified Andreasen and Andersen equation (Eq. (1)) is improved when low distribution moduli q are applied. Lower values of q result in mixes with a higher fines content that improves the compaction behavior of the mix as the friction between the coarser aggregates is reduced and, consequently, higher packing fractions are obtained that result in higher internal friction and improved green-strength. In this respect, spherical particles increased the packing fraction of the mix to a larger extent than angular particles, but reduced the green-strength due to less grain interlocking between the fines.

4 Conclusions

Based on the experimental investigations on the early-age behavior of zero-slump concrete and the obtained results, the following conclusions can be drawn:

- The early-age behavior of zero-slump concrete is mainly influenced by the granulometric properties of the fines. In this respect, the particle shape has a large impact on both compaction behavior and green-strength.
- It was demonstrated that spherical particles achieve higher packing fractions than angular particles that have the same PSD. In contrast to this, higher green-strength was achieved with mixes of angular particles although their packing fractions were lower than obtained for comparable tests using spherical particles.
- The green-strength of zero-slump concrete is a result of internal friction and adhesive forces, which are generated in the liquid bridges that are formed between the fines. It was demonstrated that the internal friction has a larger impact on the green-strength than the formation of liquid bridges. Furthermore, the particle shape and the packing fraction of the mix govern the internal friction of zero-slump concrete mixes, whereas the particle shape has a larger influence than the packing fraction. Considering a constant particle shape, higher packing fractions increase the internal friction of the mix.
- Higher packing fractions were obtained when the entire grading of the mix was optimized using the modified Andreasen and Andersen equation (Eq. (1)). In this respect, lower values of the distribution modulus q resulted in mixes with a higher fines content and a better compaction behavior. Consequently, the void fraction of the granular structure was reduced to a further extent and the green-strength was increased substantially.

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