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The Stability of Fresh Zero-Slump Concrete

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Abstract

This report focuses upon the effects of cement-substitution in part by two potash feldspar powders, and by silica-fume, on the fresh concrete strength of newly compacted cylinder samples. The water/cement-ratio was kept constant at 0.31. An Intensive Compaction Tester (abbrev: IC-Tester) which exerts a slow kneading action under pressure on the sample in a cylindrical mold, was utilized. It was found that the fresh cylinder compressive strength increased with decreasing water-content and more than doubled with each of the 3 fillers replacing 30 % of the cement-volume. A tradeoff was a loss in 28-day compressive strength for both of the feldspars, while the 28-day strength of the silica-samples remained virtually unaffected.

Keywords: Zero-slump concrete, meniscus, fresh strength, fillers, *cement-replacement*

1. Introduction

1.1 What is zero-slump concrete?

The American Concrete Institute defines zero-slump concrete as concrete with ¼ inch, or approx. 6 mm, slump or less. The compressive strength, or stability, of dry concrete, as used in the precast industry, e.g. the manufacturing of pipes, building blocks, is of importance, often more so than the cured strength, due to required re-use of molds as soon as possible subsequent to compaction. To achieve the adequate internal cohesion of the granular mass, the water-content must be low, so that the mass is unsaturated, i.e. water/air interfaces exists between particles. This increases inter-particle bonds. In addition, there is attraction due to particle electrical charges. Friction between particles also contributes to the stability. Particle shape and the density of solids content, i.e. the degree of compaction, or "packing fraction", determine the internal friction of zero-slump concrete mixes, which may have a greater impact on fresh strength than capillary forces [1].

Attention is focused on developing a concrete composition which results in fresh concrete having the required stability while also possessing acceptable workability. The influence of particle attraction due to menisci, Figure 1, and particle polarity, on the behavior of the granular substance, increases with decreasing particle size.

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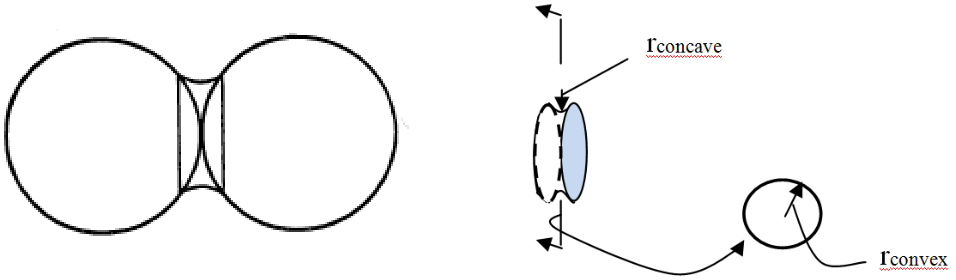


(**A**) (**B**)

Figure 1: (A) Two spherical particles moistened by a limited amount of water. In addition to existing as a film over the surface of each particle, there will be a water-body between the particles. (B) Configuration of the body of water between two moist solid spherical particles.

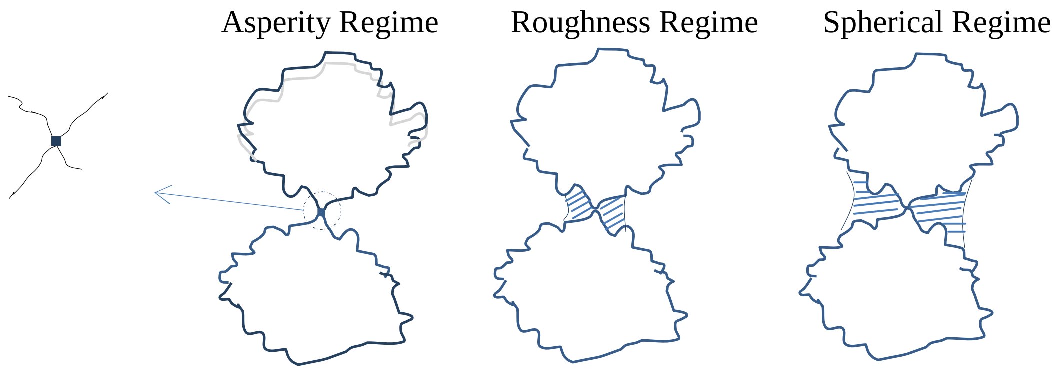
The hydrostatic pressure within the body of water between the particles may be expressed as

$$p = p_A + 2\gamma\left(\frac{1}{r_{convex}} - \frac{1}{r_{concave}}\right) \qquad \text{Eq . (1)}$$

where p_A is the atmospheric pressure, and γ represents the surface tension of water.

The hydrostatic pressure, *p*, becomes lower with decreasing volume of the body of water, because the concave radius will be diminishing at a faster rate than the convex radius. Thus, when the concave radius is small enough, the hydrostatic pressure within the body of water will become smaller than the atmospheric pressure, and increasingly so with reducing volume of the water-body. This strengthens the bond between the two particles [2]. Both polarity of particles and the surface tension of water are reduced by the addition of plasticizing agents. Accordingly, the solid density, the *packing fraction*, of fresh, zero-slump concrete, after equal compaction energy input, is affected by the particle size distribution, i.e. the grading curve, and particle shape and angularity, particle surface texture, the water content in the granular mass, and the amount of plasticizer. Optimized grading of the solids improves the packing of aggregates, and the denser granular structure yields higher strength of the fresh concrete and higher compressive strength of the hardened concrete [1].

The various shapes, and unevenness of surface (asperity), of the solids in concrete, together with the water volume per contact point between particles, affect the capillary attraction between aggregate grains. At minute moisture contents the liquid forms menisci at asperities on the surfaces of the grains, Figure 2 (A). At increasing water volumes per particle contact point, larger cohesive menisci will form at inter-grain contact points, Figures 2 (B) and (C) [3].



(A) (B) (C)

Figure 2: Three regimes of volume of water between two solid particles

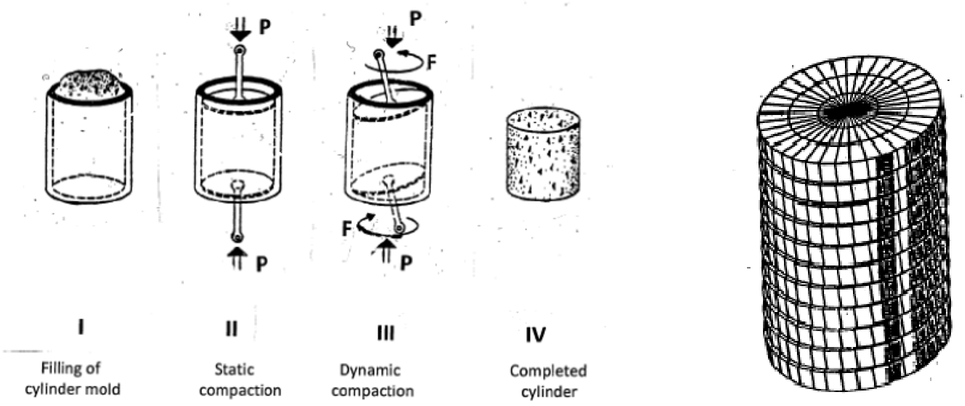
Asperity Regime: For the smallest amount of water per particle contact, the capillary force is dominated by the accumulation of fluid around a single or a small number of asperities at which two neighboring particles are in contact. [4]

Roughness Regime: For larger amounts of water per particle contact, the fluid will occupy a larger rough region, which is still small enough that the macroscopic curvature of the particle plays no role. However, the fluid occupies more than the area around a single asperity [4].

Spherical Regime: For liquid volumes exceeding the lateral dimension of several asperities, whereby the liquid bridge is influenced by the particle curvature. A further increase of the liquid volume results in an increase in the capillary force towards a limit, beyond which a further water-volume increase will result in a decreasing capillary force [4].

In addition to fluid in the contact region, the water will have wetted the surface of the particle. Thus, there will be a layer of fluid, normally not thicker than a few monolayers (monolayer = single layer of atoms or molecules adsorbed on a surface). Hence, there is a complicated set of forces between this film and the surface [4].

1.2 The Intensive Compaction Tester



(A) (B)

Figure 3: The operating principle of the IC-Tester (A), and the shear compaction principle of the IC-Tester (B).

With the Intensive Compaction Tester, or IC-Tester, the properties of zero-slump, granular earth-masses in general, may be investigated, Figure 3 A. The cylinder sample, diameter 100 mm, approx. volume: 0.8 dm^3 [5], is compacted by exertion of pressure and cyclic shearing during a continuous kneading action. The kneading action causes shear planes to develop in the granular mass, Figure 3

B. Due to this, and to the applied compaction force, the particles within the mass relocate relative to each other into more favorable positions, whereby air is being expelled. Upon completion of the compaction, a printout is obtained, which gives the amount of work exerted by the machine to compact the sample to specified densities. The cylinder may be compression-tested or split-cylinder tested at any age [5, 6]. The apparatus is reliable for research and developing work in laboratories, and for solving production challenges in industry, and has been used successfully for evaluation of different qualities of sand for use in zero-slump concrete and for improving on zero-slump concrete mixes for highway construction [7]. According to the manufacturer, Invelop OY, Finland, it is possible, with the IC-Tester, to identify changes in the granular mass corresponding to those caused by 3 – 5 liters of water pr. m^3 of concrete [8].

1.3 Purpose

The aim of this report, which is based on the doctoral thesis "Zero-Slump Concrete: Degree of Compaction and Strength. Effects of Fillers as Part Cement-Replacement" [9], is to focus upon the correlation between fresh strength, air content, cement filler-replacement amounts, workability and 28-day compressive strength. The materials were as used in the concrete-making industry, as the goal was to obtain information applicable to cement-users. Therefore a practical approach to the results is taken. A thorough investigation of the effects of surface texture and shape of particles on the degree of compaction on fresh strength was considered to be outside the scope of the thesis on which this paper is based.

2. Materials

2.1 Fillers used as part cement substitution

Two gradations of Potash Feldspar, designated NGP-120 and NGP-325, were utilized as fillers to partially replace cement, NGP-120 being the coarser of the two, while the NGP-325 had a particle size distribution close to that of the RP-38 cement used.

Table 1: Percentage-values retained at each "sieve" according to results from "CILAS-test" (Granulometre 226, Compagnie Industrielle des Lasers), with computed fineness moduli and Blaine-values.

Sieve-size	*Cement RP-38*	*Feldspar NGP-120*	*Feldspar NGP-325*
120	0	0	0
64	0	12.25	1.65
32	8.15	33.60	12.50
16	35.90	57.85	37.75
8	59.65	72.55	58.65
4	76.80	84.10	74.85
2	88.60	92.75	88.30
1	93.30	97.75	96.40
0	100.0	100.0	100.0
Fineness Modulus	3.63	4.41	3.70
Blaine (m^2/kg)	445*	352	583*

*The seemingly non-corresponding Blaine-values of Cement RP-38 and Feldspar NGP-325 are likely caused by particle shape differences.

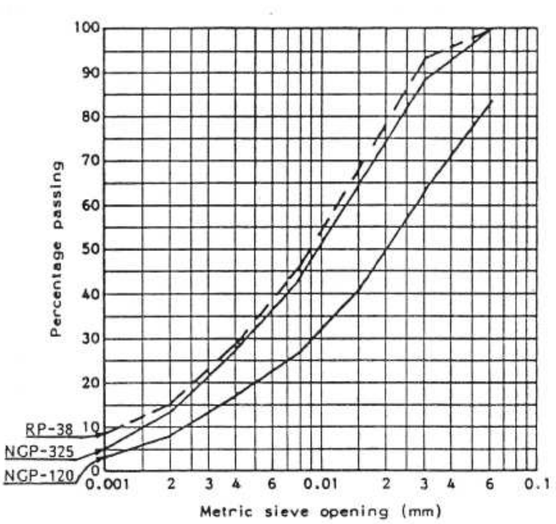


Figure 4: Particle size distribution curves for the two gradings of Potassium Feldspar utilized, and of Cement RP-38.

2.2 Sand and coarse aggregates

A 50/50 combination of sand/coarse aggregate was used, as this proved to be a nearly optimum combination for achieving a low aggregate voids content.

2.2.1 Sand

Natural sand of type designation “Årdal” was used. This sand contained mostly well-rounded cubical grains. The particle size was 0 – 8 mm.

The sand particle size distribution curve is illustrated in Figure 5. This was a typical grading of sand used for pre-stressed concrete production.

2.2.2 Gravel (coarse aggregate)

Crushed stone of type designation “Durasplitt” of particle size 8 – 11 mm was utilized. The coarse particle distribution is depicted in Figure 5.

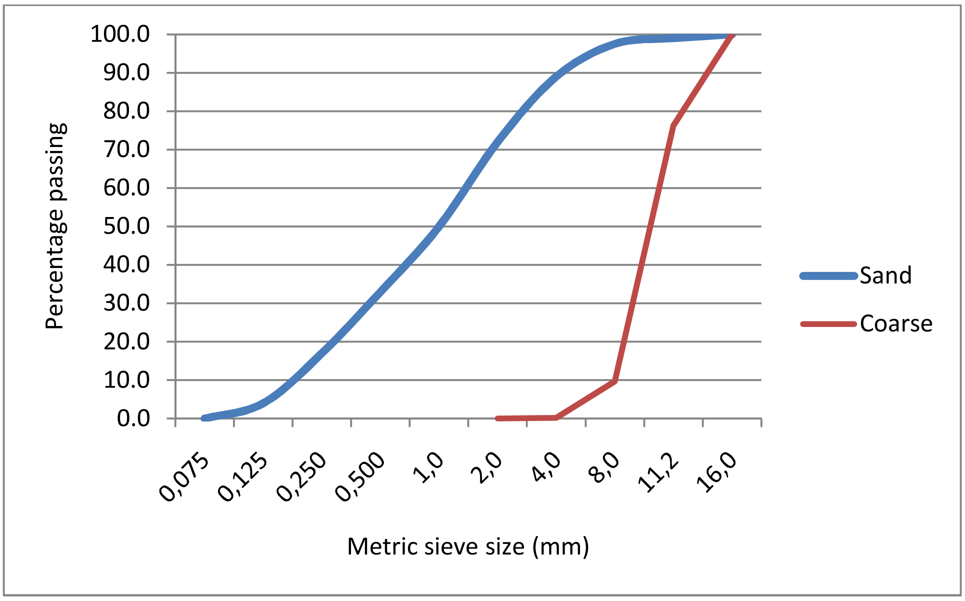


Figure 5: Particle size distribution in the sand and coarse aggregate used.

2.3 Plasticizer

The amount, 0.8% of the base mix cement content, or 4.1 kg of dry powder of superplasticizer of Scancem designation SP-67, was added to all mixes. This was a modified condensation product of melamine formaldehyde, which was claimed by the manufacturer to have a strong plasticizing effect on newly mixed concrete [9].

3. Experiments, results and discussion

3.1 Base Mix

The mix composition in Table 2 was arrived at as the composition resulting in the highest solid density after 80 cycles of compaction at 4 bars pressure setting.

Table 2: Concrete mix composition

Cement RP-38	*516.0 kg/m^3*	
Water	160.0	"
Natural sand (0 – 8 mm)	925.0	"
Crushed rock (8 – 16mm)	925.0	"
Superplasticizer (melamine) Scancem SP-67 dry	4.1	"

3.2 Cement replacement and compaction by IC-Tester

The w/c-ratio was kept constant at 0.31 throughout the experiments, while the replacement-percentages were 0, 2, 5, 10, 20, and 30%. 80 compaction cycles, and a pneumatic cylinder pressure setting of 4 bars , corresponding to 1.6 bars pressure exerted on samples, were used [5].

3.2.1 Air- and water-content in mixes after 80 compaction-cycles

According to the results listed in Table 3 (silica), Table 4 (NGP-120) and Table 5 (NGP-325), the air content increases with the replacement percentages. At 30% replacement the air content is higher with the NGP-325 than with the coarser graded NGP-120, reflecting the influence of filler-particle size on the water-menisci configuration. The silica-samples had only half the air-content of the NGP-120-samples, probably due in part to its lubricating-and water-replacing effect.

Table 3: Percentages air- and water-contents at cement replacement-percentages by silica-fume after 80 compaction cycles

	Percentages air- and water- contents					
	Replacement percentages by silica					
w/c=0.31	0	2	5	10	20	30
Air	0.5	0.6	0.6	0.8	1.4	2.1
Water	15.9	15.7	15.3	15.0	14.0	12.9

Table 4: Percentages air- and water-contents at cement replacement-percentages by feldspar NGP-120 after 80 compaction cycles

	Percentages air- and water-contents					
	Replacement percentages by NGP-120					
w/c=0.31	0	2	5	10	20	30
Air	0.5	0.6	0.7	1.0	1.6	4.1
Water	15.9	15.7	15.5	15.0	13.9	12.6

Table 5: Percentages air- and water-contents at cement replacement-percentages by feldspar NGP-325 after 80 compaction cycles

	Percentages air- and water-contents					
	Replacement percentages by NGP-325					
w/c=0.31	0	2	5	10	20	30
Air	0.5	0.5	0.6	0.8	1.9	5.2
Water	15.9	15.7	15.5	15.0	13.9	12.5

3.2.2. Compaction work exerted

At 30% replacement, the resistance to compaction complies with the amount of air remaining in the samples, ref. section 3.2.1, i.e. more air means stronger menisci-forces. Ref. Table 6.

Table 6: Work in Nm x cycles exerted by the Intensive

Compaction Tester on zero-slump concrete test-samples during 80 cycles of kneading compaction.

w/c = 0.31	Compaction work exerted (Nmxcycles)					
Replacement filler	Replacement percentages					
	0	2	5	10	20	30
Silica-fume	1051	960	808	733	907	1520
Feldspar NGP-120	1051	1074	1448	1493	2362	2930
Feldspar NGP-325	1051	1199	1381	1421	2248	3175

3.2.3. Fresh compressive strengths

The values listed in Table 7 indicate that, at 20 and 30% replacement, higher air content, ref. Section 3.2.1, yields increased fresh strength.

Table 7: Fresh, zero-slump concrete compressive strength

w/c = 0.31	*Fresh concrete compressive strength (N/mm^2)*					
Replacement filler	Replacement percentages					
	0	2	5	10	20	30
Silica-fume	2.25	2.15	2.14	2.25	2.85	4.66
Feldspar NGP-120	2.25	2.04	2.76	3.30	4.53	4.84
Feldspar NGP-325	2.25	2.58	2.84	3.32	4.57	4.91

3.2.4 28-day compressive strengths

The 28-day compressive strength values in Table 8 confirm that the cured strength decreases with increasing fresh sample air-content, ref. section 3.2.1.

Table 8: Zero-slump concrete 28-day cylinder compressive strengths in MPa

w/c = 0.31	28-day compressive strength (N/mm^2)					
Replacement filler	Replacement percentages					
	0	2	5	10	20	30
Silica-fume	54.4	50.8	51.9	57.4	56.6	54.1
Feldspar NGP-120	54.4	49.1	49.9	47.1	49.8	45.5
Feldspar NGP-325	54.4	52.0	51.6	53.0	48.2	42.4

4. Summary and discussion

4.1 Compaction energy, air content and fresh strength

4.1.1. Mixes with silica-fume as part cement-replacement

Generally, ref. Table 9, there is a correlation between the compaction energy (work exerted) and the fresh compressive strength of the silica-mixes. The fresh concrete strength increases considerably at the higher replacements-percentages, as does the fresh concrete air content. This reflects the higher number of contact points, which means more menisci and also increased inter-particle friction and electrostatic attraction.

4.1.2 Mixes with cement replaced in part by respectively Feldspar NGP-120 and NGP-325

The lower compaction energy during 80 cycles with 30% replacement NGP-120 (Table 10) than with the more finely graded NGP-325 (Table 11) is likely due to more contact points between particles with the latter, i.e. more inter-particle friction and stronger capillary forces due to less water per contact point and a higher number of menisci in the mass. The higher fresh strength with the NGP-325 could probably also be caused by the aforementioned factors. The fresh concrete strength increases with increasing air voids contents, likely due to the meniscus-forces becoming stronger with decreasing water-content.

4.1.3 Air-content in silica-mixes versus air-content in feldspar-mixes

At the higher replacement-percentages, the air-contents in the fresh samples were considerably higher in the feldspar-mixes than in the silica-mixes. This is likely due to the water replacing ability of the silica-powder and the lubrication (“roller-bearing effect”) by the silica.

4.2 Cured strength

4.2.1 Mixes with silica-fume as part cement-replacement

Silica-samples: In spite of 2.1% air content in the fresh silica samples, Table 9, their 28-day compressive strengths are not significantly reduced, which is likely due to the pozzolan-effect, i.e. the $SiO_2/Ca(OH)_2$ - reaction. The silica-samples also have the highest relative solid density of all samples with 30% replacement after 80 compaction-cycles, Table 12.

4.2.2 Mixes with cement replaced in part by respectively Feldspar NGP-120 and NGP-325

Contrary to the fresh strength, with feldspars NGP-120 and NGP-325, the cured strength decreases with decreasing solid density, as the less closely packed the particles are, the greater the hydration products “hook up” distances becomes [10, 11].

The 28-day compressive strengths are considerably lower, respectively 84% and 78% of the no-replacement samples for feldspar 120 and 325, reflecting the high fresh sample air contents, 4.1% and 5.2% respectively.

Table 9: 80 compaction cycles with *silica-fume* as cement replacement: fresh strength, workability, cured strength.

Cement Replacement Percentage	*Air Content (%)*	*Work exerted (Nm x cycles)*	*Fresh Compressive Strength (Mpa)*	*28-Day Compressive Strength (Mpa)*
0	0.5	1051	2.25	54.4
2	0.5	960	2.15	50.8
5	0.6	808	2.14	51.9
10	0.8	733	2.25	57.4
20	1.4	907	2.85	56.6
30	2.1	1520	4.66	54.1

Table 10: 80 compaction cycles with feldspar *NGP-120* as cement replacement: fresh strength, workability, cured strength.

Cement Replacement Percentage	*Air Content (%)*	*Work exerted (Nm x cycles)*	*Fresh Compressive Strength (Mpa)*	*28-Day Compressive Strength (Mpa)*
0	0.5	1051	2.25	54.4
2	0.6	1074	2.04	49.1
5	0.7	1448	2.76	49.9
10	1.0	1493	3.30	47.1
20	1.6	2362	4.53	49.8
30	4.1	2930	4.84	45.5

Table 11: 80 compaction cycles with feldspar *NGP-325* as cement replacement: fresh strength, workability, cured strength.

Cement Replacement Percentage	*Air Content (%)*	*Work exerted (Nm x cycles)*	*Fresh Compressive Strength (Mpa)*	*28-Day Compressive Strength (Mpa)*
0	0.5	1051	2.25	54.4
2	0.5	1199	2.58	52.0
5	0.6	1381	2.84	51.6
10	0.8	1421	3.32	53.0
20	1.9	2248	4.57	48.2
30	5.2	3175	4.91	42.4

Table 12: Condensed results

Repl. by	*Blaine*	*Cement Repl. %*	*Volume-% Air*	*Volume-% Water Content*	*Relative Solid Density*	*Work exerted (Nm x cycles)*	*Fresh Comp. Str. (Mpa)*	*28-Day Comp. Str. (Mpa)*
Cement (No repl.)	445	0	0.5	15.9	0.836	1051	2.25	54.4
Silica-fume	15000 - 20000	30	2.1	12.9	0.850	1520	4.66	54.1
Feldspar NGP-120	352	30	4.1	12.6	0.833	2930	4.84	45.5
Feldspar NGP-325	583	30	5.2	12.5	0.823	3175	4.91	42.4

5. Conclusions

The fresh cylinder strength tests do indicate the existence of a correlation between the air-content and fresh zero-slump concrete stability, or that the stability of the newly molded product will increase with increasing air-voids volume. This is also reflected by the greater compaction work required for the feldspar-specimens. The lubricating property of silica-fume, likely due to its water replacement ability and “roller-bearing effect”, reduces the compaction effort required on the silica-samples.

The fresh concrete compressive strengths more than doubled with each of the 3 fillers replacing 30 % of the cement-volume, but at the tradeoff of a loss in 28-day compressive strength for both of the feldspars. If this is not acceptable to a manufacturer, a solution might be to use a combination of silica-fume and feldspar as part cement-replacement as the 28-day compressive strength of the silica-samples remained basically unchanged.

6. Acknowledgements

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