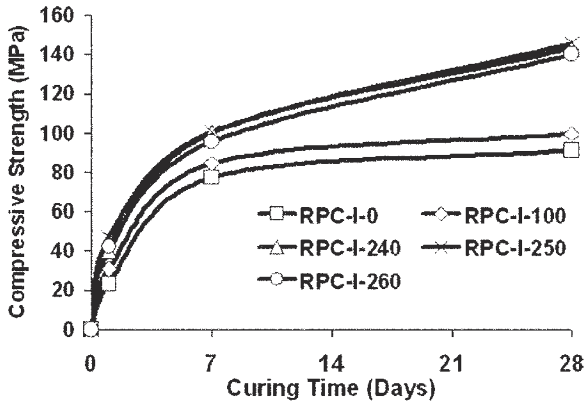

Figure 2—Compressive strength of RPCs with different silica fume dosages.

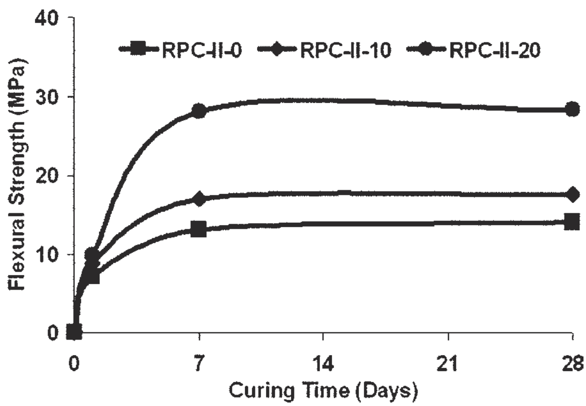

Figure 3—Flexural strength of RPCs with fiber dosages vs. curing time.

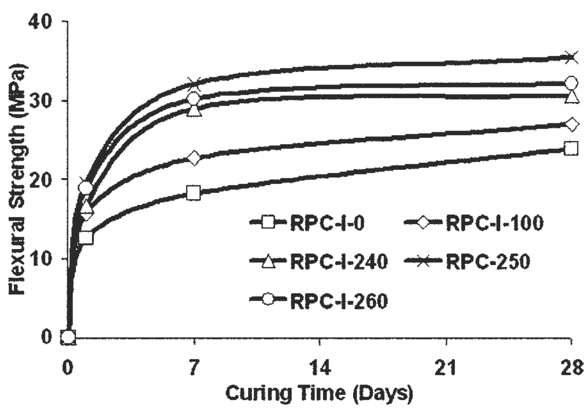

Figure 4—Flexural strength of RPCs with different silica fume dosages vs. curing time.

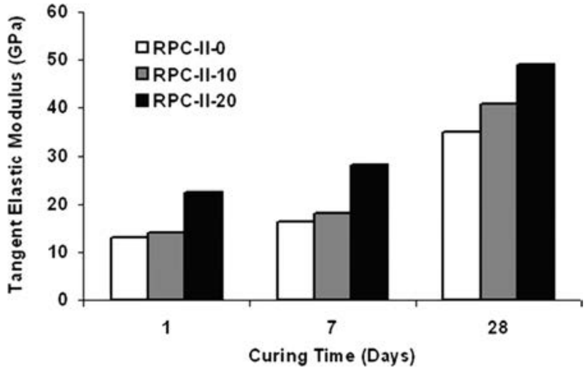

Figure 5—Elastic modulus of RPCs with different fiber dosages vs. curing time.

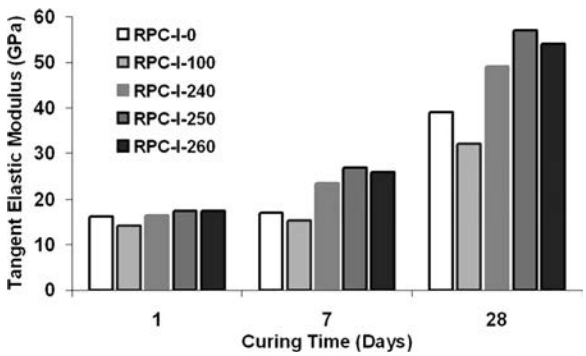

Figure 6—Elastic modulus of RPCs with different silica fume dosages vs. curing time.

Optimization of Mixture Proportions of Normal, High-Performance and Self-Compacting Concrete

by B. Persson

Synopsis: This article outlines an experimental and numerical study on the optimization of mixture proportions of concrete. For this purpose about 500 mixture proportions were studied in the laboratory and compared with about 500 mixture proportions from industry. Normal, high-performance and self-compacting concrete were included in the investigation. Additives such as fly ash, limestone filler, silica fume and slag and different kinds of cement were included in the program. The *w/c* varied between 0.15 and 1, with 28-day cylinder strength ranging from 20 to 120 MPa. The results show with high significance that ideal particle distribution curves exist for each cement and concrete type taking into account also the related water demand and the correlation between *w/c* and strength. The study resulted in a highly efficient commercially available computer program.

Keywords: concrete; high-performance concrete; ideal grading of particles; mixture proportions; self-compacting concrete

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BACKGROUND AND OBJECTIVE

The interest in using of self-compacting concrete (SCC), and high-performance concrete (HPC) is increasing rapidly in order to solve modern work-environment conditions and construction moisture problems. Presently SCC is used in 50% of the precast market in Sweden, in some factories as much as 100%. About 7 million square metres of HPC for flatwork such as slabs in dwelling houses have been cast in the last decade, also a way of increasing construction speed since molds may be removed earlier with HPC than with normal concrete (NC). For both SCC and HPC, the particle grading is of the utmost importance since it characterises all the concrete materials in one way. The number of different materials required to produce SCC and HPC is extended compared with NC, which require a simple tool to determine the mixture proportions. Another factor involved in justifying the use of particles distribution for mixture proportions is the shortage of natural resources; natural sand and gravel are no longer available close to city areas. In Sweden, taxes on natural resources make the situation even more urgent to resolve. The last great factor is the human environment, especially the greenhouse effect, mostly related to the release of industrial carbon dioxide to the atmosphere. About 7% of the release of industrial carbon dioxide is related to the production of cement [1]. It is therefore of great importance to arrange the particles in concrete to produce grading curves without gaps or convex shapes since they create a need for more fine particles, which in turn increases the cement content [2]. Convex particle size distribution curves lead to gaps on both sides, which also increases the requirement for more fines [3]. For NC and HPC, ideal distribution of particles in fresh concrete was established more than a decade ago [4]. Later on, similar curves were found to exist for SCC [5]. For SCC the particle grading seems be of greater importance than for NC and HPC. The objective of he present study was to establish the fundamental basis for an ideal grading of particles in fresh concrete and to develop the optimum grading curves for SCC.

PREVIOUS RESEARCH

Theoretical aspects

Most models of the effect of materials on mixture proportions of concrete are related to the cement paste and its properties [6]. Previously, once the workability and the volume of the cement paste was satisfactory, no further attention was paid to the effect of other materials, of the concrete which in fact occupy perhaps 80% in the concrete volume, i.e. filler, sand, gravel and stone. Presently, packing of other materials besides cement particles therefore becomes a key for HPC [7] and probably also for SCC. By using a continuous grading, the wall effect with more porous zones in the concrete is minimized [8], i.e. the volume between aggregate particles and bulk paste is filled with different sized materials that interact to give an ideal grading. However, limits have to be set on the minimum porosity, otherwise it will be reached with the maximum size of aggregate but is not suitable for concrete workability [9]. The other approach using the matrix model leads to absence of aggregate [10], which in turn is not feasible due to its brittleness, huge shrinkage, high cost and so forth.

Empirical consequences

Analyses were performed on differences of particle grading in fresh concrete of about 500 different mixes. In reference [4] the following particle grading of fresh NC and HPC was established (Fig. 1):

$$s = a \cdot d^{b} \; \{0.125 < d < 0.7 \cdot d_{max}\} \qquad (1)$$

where s denotes the percentage particles passing through, a = 38%, b denotes a constant according to Table 1, d is the particle size given in Eq. 1, i.e. $< 0.7 \cdot d_{max}$ ($0.1 < d < 10$ mm) and K is the cube concrete strength (MPa). Particle grading was obtained for about 500 SCC mixtures, (Fig. 2) Table 2 [5]. NC followed more or less the grading shown in Fig. 1, i.e. much fewer fines than in SCC. More fines are required in SCC to avoid segregation. Table 2 gives the particle distributions obtained following Eq. (1). For NC and sieve sizes varying between 0.063 mm and 16 mm a = 37% and b varies between b = 0.24 (corresponding to K60 (MPa)) and b = 0.35 (corresponding to K30 (MPa)). For sieve sizes varying between 0.063 mm and 16 mm and SCC without fibres, a = 47% with b varying between b = 0.24 (K60) and b = 0.27 (slightly more inclined for K30) [5]. The factor a represents the particle passing through at 1 mm, For sieve sizes varying between 0.063 mm and 16 mm and SCC with 2 kg/m³ of 32 μm polypropylene fibres (ppf) (or 1 kg/m³ of 18 μm ppf), a value of a = 48% was obtained with b varying between b = 0.23 (for K60) and b = 0.26 (for K30). The conclusion in reference [5] was that more fines were required in SCC than in NC, i.e. about 10% more particles less than 1 mm or about 220 kg/m³ more fines. For SCC corresponding to the cube strength class K60, the inclination of the distribution of particles in fresh concrete was more or less the same as in NC, b = 0.24, but for K30 less inclination of the grading curve was observed in SCC than in NC. For SCC with 4 kg/m³ ppf, values of a = 55% and b varies between b = 0.24 (K60) and b = 0.27 (K30). Japanese experience indicated a = 50% and b = 0.26, i.e. fewer fines and a steeper grading curve [12,13][1]. The following should be used when constructing a grading curve for fresh SCC without fibres as described by Eq. (1) (K = cube strength,MPa):

1. a = 47%
2. b = 0.27 (K30)
3. b = 0.24 (K60)

With 2 kg/m³ of 32 μm ppf (or 1 kg/m³ of 18 μm ppf) in the SCC, the following constants are recommended:

1. a = 48%

[1] Sakata, K., Personal communication, Okayama University, Okayama, 1998.

2. b = 0.26 (K30)
3. b = 0.23 (K60)

With 4 kg/m³ of 32 µm ppf (or 2 kg/m³ 18 µm ppf) the following constants were found:

1. a = 55%
2. b = 0.27 (K30)
3. b = 0.24 (K60)

Too little cement + filler in SCC gave a segregation risk, i.e., too low of an a-value in Eq. (1). Too low of a slope of the grading curve gave a high risk of blocking of SCC with 4% fibres.

EXPERIMENTAL RESULTS

Strength relationships

One parameter in order to set the particle distribution was the water-cement ratio, w/c. About 500 mixture proportions of three different cements, A ("Anläggning"), B ("Byggcement") and S ("Slite SH") or SCC mixtures were related to w/c. The following Eqs. were developed to relate the required w/c to the cylinder strength (C) and the air content (AC) for 1 < AC < 6% and 20 < C < 120 MPa:

Cement A:

$$w/c=(-0.625\cdot AC+6.67)\cdot C^{(0.024\cdot AC-0.745)} \quad (2)$$

Cement B:

$$w/c=(-0.636\cdot(AC)^2+4.58\cdot(AC)-1.89)\cdot C^{(0.0381\cdot(AC)^2-0.278\cdot(AC)-0.251)} \quad (3)$$

Cement S :

$$w/c=(1.075\cdot AC+1.76)\cdot C^{-(0.0655\cdot AC+0.460)} \quad (4)$$

SCC:

$$w/c=(-0.97\cdot AC+7.45)\cdot C^{(0.0683\cdot AC-0.7788)} \quad (5)$$

Water content

Another parameter necessary to set the particle size distribution is the water content, w, (kg/m³). The following Eqs. were developed:

Cement A: $w = 148\cdot(w/c) + 104$ (6)

Cement B: $w = 87\cdot(w/c) + 137$ (7)

Cement S: $w = 87\cdot(w/c) + 148$ (8)

SCC: $w = 163\cdot(w/c) + 107$ (9)

Particle size distribution

The distribution of filler particles sizes passing through between 0.001 mm and 0.125 mm is (%, $p_{0.125}$ = content of filler and cement (%):

$$p_{0.001-0.125} = (-225.01\cdot d^2 + 27.937\cdot d)\cdot p_{0.125} \quad \{0.001 < d < 0.125 \text{ mm}\} \quad (10)$$

The content of filler and cement, i.e. the particles smaller than the sieve size 0.125 mm, $p_{0.125}$, was estimated with the following Eq. (%,C = cylinder strength (MPa)), Fig. 3:

$$p_{0.125} = 5.9455\cdot \ln(C) - 1.876 \quad \{20 < C < 120 \text{ MPa}\} \quad (11)$$

In order to estimate the distribution of particles greater the sieve size 0.125 mm it was necessary to define standard sieve sizes above 0.125 mm, i.e. 0.25, 0.5, 1, 2, 4, 5.6, 8, 11.2, 16, 23 and 32 mm. The percentage of particles passing through between 0.125 mm and the second maximum aggregate standard size, s, i.e. for example 8 mm when the maximum sieve size is 16 mm, were estimated with the following Eqs. dependent on the maximum aggregate size (%):

Max 8 mm:

$$p_{0.125\text{-}s} = p_{0.125} + (p_s - p_{0.125})\ 0.2885 \cdot \ln(d) + 0.6 \qquad (12)$$

Max 11 mm:

$$p_{0.125\text{-}s} = p_{0.125} + (p_s - p_{0.125}) \cdot 0.263 \cdot \ln(d) + 0.5469 \qquad (13)$$

Max 16 mm:

$$p_{0.125\text{-}s} = p_{0.125} + (p_s - p_{0.125}) \cdot 0.2404 \cdot \ln(d) + 0.5 \qquad (14)$$

Max 23 mm:

$$p_{0.125\text{-}s} = p_{0.125} + (p_s - p_{0.125}) \cdot 0.2225 \cdot \ln(d) + 0.4626 \qquad (15)$$

Max 32 mm:

$$p_{0.125\text{-}s} = p_{0.125} + (p_s - p_{0.125}) \cdot 0.2061\ \ln(d) + 0.4286 \qquad (16)$$

The percentage of particles passing through the second next maximum aggregate standard size, s, i.e. for example 5.6 mm with the largest size being 11.2 mm, was estimated with the following Eq. (%, C = cylinder strength (MPa)), Fig. 4:

$$p_s = -5.9455 \cdot \ln(C) + 83.876 \qquad (17)$$

For the next maximum aggregate sieve size, i.e. for example 11.2 mm when the maximum size is 16 mm, the particle distribution was estimated with the following Eq. (%, p_s = particles passing through the second next largest aggregate standard sieve size, s, (%)):

$$p_{s+I} = (p_s + 100)/2 \qquad (18)$$

DISCUSSION AND FIELD APPLICATIONS

Strength relationships and water content

The amount of air and cement type has a great influence on the strength of concrete, as given by Eqs. 2 through 5 and as shown in Figs 5 through 8. The water-cement ratio and the cement type has a great influence on the water content, as given by Eqs. 5 through 9 and as shown in Fig. 9. For SCC, the filler content in order to avoid segregation had a great influence on the water requirement, especially at high w/c. At low w/c, almost no filler was required to avoid segregation in SCC, i.e. the aggregate was held in place only with the influence of cement.

Field applications

The Eqs. (1) through (18) were applied to new mixture proportions for Abetong ready-mixture production where natural gravel was replaced with crushed stone, also for small sizes [14,15][2]. Lately the grading curve of the natural gravel used at the Abetong factories has deteriorated because of the lack of fine material [14]. Concern has been voiced that this could affect the rheology of the concrete, and that is why the particle size distribution has been reviewed [14]. The possibility to partially replace natural gravel with crushed stone has also been examined as this is an environmental goal of Abetong [14]. In the optimization, two new materials were introduced, crushed stone to replace the natural gravel and sand filler, which was chosen to fill a leap in the sieve grading curve [14]. Seven mixture designs have been tested in 25-litre batches at Abetong's factory in Vislanda, where the rheology was measured with a slump cone [14]. The results show a decreased water requirement in the optimized mixture proportions despite the replacement of natural gravel with crushed stone [14]. A complementary test of a mixture without sand filler was also performed and the results showed no deterioration in performance. The conclusion was drawn that sand filler is unnecessary [14]. Finally a mixture where all natural gravel was replaced with crushed stone was tested. The mixture gave good results, probably because of the increased quantity of fine material in the crushed stone [14]. An overview of the actual concrete strength and the strength requirements showed that there is a possibility to decrease the amount of cement. Together with the replacement of natural gravel with crushed stone, this could give a significant decrease in production costs. Parallel to this, the distributions of particle sizes were optimized, which gave the following results [14,15]:

1. Slightly lower cement content
2. Lower requirement of superplasticiser
3. Lower requirement of air-entrainment agent
4. Improved workability

CONCLUSIONS

This article outlines a theoretical and experimental investigation of the ideal distribution of particle sizes in fresh concrete. For this purpose more than 1000 laboratory experiments and about 500 field tests on the workability of concrete were performed along with strength tests. The result indicates the following conclusions:

1. Optimal linear-logarithmic grading curves related to maximum workability and minimum cement content exist for normal concrete and high-performance concrete dependent on cement type, compressive strength and air content.
2. For self-compacting concrete the same dependences exist except for the relation to cement type, which is not a factor for self-compacting concrete.
3. The accuracy of an optimum grading of particles in concrete has been validated by field tests and comparisons between predictions and measurements in an extensive series of data.

[2] Lillieblad, J., Personal communication, Abetong, Växjö, 2005.

4. Slightly lower cement content, lower dosage of superplasticizer, lower dosage of air-entraining agent, and improved workability were achieved.

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