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A Particle Packing Method for Pumpable Low-Shrinkage Flowing Concrete

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In this paper, the applicability of the modified Andreasen and Andersen (A&A) particle packing model for designing pumpable flowing concretes, according to ACI 211.9R-18, is analyzed. An experimental investigation is undertaken to evaluate consistency, compressive strength, and shrinkage of flowing concretes designed with this model. The results show that the modified A&A model optimizes the particle size distribution of concrete ingredients and produces pumpable concretes according to ACI 211.9R-18. The distribution modulus of the model controls the combined grading, the ratio of coarse-to-fine aggregate, and the percentage of fine aggregate passing 300 and 150 μm. At a distribution modulus of 0.35, the model serves as the ACI's recommended boundary limit for ideal-for-pumping combined grading. A high distribution modulus results in a high coarse-to-fine aggregate ratio and lowers the drying shrinkage of concrete. This insight enables a straightforward mixture design methodology that results in concrete that meets ACI 211.9R-18 recommendations.

Keywords: flowing concrete; mixture design; modified Andreasen and Andersen (A&A) model; particle size distribution; pumpability; shrinkage.

INTRODUCTION

Concrete is the most widely used material worldwide for several primary reasons: 1) outstanding resistance to water and fire; 2) low production and maintenance cost; and 3) the ease with which it can be shaped while casting.[1] Three major concrete types used in the construction industry are conventional vibrated concrete (CVC), flowing concrete (FC), and self-consolidating concrete (SCC).[2] The main difference between these concrete types is flowability.[3] CVC typically has less than 100 mm slump and high yield stress.[4] As a result, it demands highly rapid vibratory impulses to become liquified and consolidated.[5] On the other hand, SCC has very high flowability with almost no yield stress in a way that it only demands the action of gravity to consolidate.[6] Although SCC offers significant benefits over CVC in terms of labor cost, noise nuisance, and formwork wear and tear, it is more costly.[7,8] Furthermore, SCC requires a high-range water-reducing admixture (HRWRA), finer aggregate grading, and incorporating fine materials (powders) into the mixture.[9] Some SCC mixtures also require viscosity-modifying admixtures (VMAs), although the use of a VMA is not always essential[10,11] and sometimes may cause conflicts with the HRWRA.[12] These requirements raise the cost and increase concrete shrinkage and cracking susceptibility, making SCC less desirable for applications where low shrinkage is the primary concern (for example, industrial concrete floors).[13] These shortcomings have generated considerable interest in another type of concrete, namely FC.

According to ASTM International and the American Concrete Institute (ACI), FC is a concrete mixture that retains its cohesiveness at a slump greater than 190 mm.[14,15] European standards use the flow table test[16] for classifying concrete into six classes: F1 to F6.[17] Though the flow table test[16] of the European standards is different than the slump test of ASTM,[14,15] one might classify FC as a concrete in the range of F3 to F6.[17] Contrary to SCC, FC does not require reducing the maximum size of aggregates or modifying the proportion of fine to coarse aggregate in a mixture. In addition, as the yield stress and viscosity of FC are not as low as that of SCC, there is no need to add VMAs or fines to improve viscosity while retaining low yield stress in FC mixtures. As a result, compared to SCC, FC is less costly, has less shrinkage, and less cracking susceptibility. FC provides significant benefits over CVC, too. It is proportioned with normal aggregate sizes, but at the same time, it can flow into highly congested areas. It is significantly more flowable than CVC and requires far less vibration to consolidate, too. As a result, compared to CVC, FC increases production rates, reduces noise nuisance, lowers labor cost, and increases mold lifetime.

There are, however, several major obstacles related to the design and use of FC. First, in comparison to CVC and SCC, the mixture design method and particle-size distribution (PSD) of FC remain largely understudied. The PSD highly affects the rheological and mechanical properties of concrete.[18,19] The PSD determines the particles' mixture void content and the paste's volume needed to fill the voids.[20] In addition, the PSD determines the specific surface area of the particles and the volume of the paste required to coat aggregates. Several particle packing models have been introduced to maximize the density of granular skeleton and to design CVC mixtures.[21-23] Although these proportioning methods give satisfactory results for designing low-to-medium-slump CVC mixtures, they do not necessarily result in highly workable cohesive FC mixtures. This shortcoming is mainly because CVC mixtures are designed for high density and low paste volume, while FC mixtures are designed for high flowability and cohesiveness.

On the other hand, the limited research on FC is based on maximum density and does not consider the combined

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grading of particles on the mixture's flowability. Hendrix and Trejo[24] presented an FC mixture proportioning method based on the paste-to-aggregate volume ratio. Su and Miao[25] proposed a mixture design method for FC mixtures based on packing factor, which is the ratio of the mass of aggregates in the mixture to that of a loosely packed state. They suggested that the aggregate packing factor determines the aggregate content and affects the workability of concrete.[25] A much more systematic approach that identifies how combined grading interacts with the mixture's flowability remains unreported.

Furthermore, the limited research on FC does not provide information on the pumpability or shrinkage of the mixture design method. In many critical applications, low-shrinkage concrete needs to be pumped off. Much of the current literature on the pumpability of concrete pays particular attention to the formation of the lubrication layer and its effect on the pumpability of concrete.[26,27] ACI's guide to selecting proportions for pumpable concrete provides numerical guidelines on optimum aggregate grading and fine content that lead to the most efficient pumping results.[28] At the current state-of-the-art, one approach to designing a pumpable concrete mixture is to compare the final mixture design to ACI 211.9R-18 recommendations.[28] It would be more convenient to have a mixture design method with ACI 211.9R-18 guidelines[28] at its heart. However, such a method remains unreported.

This paper aims to provide solutions to these obstacles. First, the main results from the literature regarding the maximum particle packing and flowability of the modified Andreasen and Andersen (A&A) model[29] are presented. Next, the model is adapted to the specific case of concrete and compared and contrasted with the technical recommendations of ACI 211.9R-18.[28] It is shown that the modified A&A model is highly compatible with ACI's experimental data. At the distribution modulus of 0.35, this model gives the boundary limit for ideal pumpability. Moreover, the pumpability and application of the modified A&A model at lower distribution moduli are reported. Finally, the modified A&A model is used to design FC mixtures. The fresh and hardened properties of the FC mixtures such as flow diameter, compressive strength, and drying shrinkage are reported. The present research establishes that the modified A&A model is highly compatible with ACI's experimental data on pumpability. Furthermore, using this model for designing the whole concrete mixture (aggregates and powders) at a suitable distribution modulus leads to flowing concrete with low shrinkage.

RESEARCH SIGNIFICANCE

ACI 211.9R-18 provides numerical guidelines on optimum aggregate grading and fine content that lead to the most efficient pumping results. On the other hand, the modified A&A model is a well-known method to maximize particle packing in concrete mixtures. This detailed study establishes a relationship between ACI 211.9R-18 and the modified A&A particle packing model to make low-shrinkage pumpable flowing concrete. Such data can be of interest to contractors and concrete technologists and the authors recommend incorporating this relationship in the next version of ACI 211.9.

ANALYTICAL INVESTIGATION

Modified A&A model

One approach to achieving the maximum particle packing in concrete mixtures is using the modified A&A model[20,30] as expressed by

$$P(d) = \frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q} \tag{1}$$

$$RSS = \sum_{i=1}^{n} \left[P_{mix}(d_i^{i+1}) - P_{target}(d_i^{i+1})\right]^2 \rightarrow \min \tag{2}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left[P_{mix}(d_i^{i+1}) - P_{target}(d_i^{i+1})\right]^2}{\sum_{i=1}^{n} \left[P_{mix}(d_i^{i+1}) - \overline{P_{mix}}\right]^2} \forall d_i^{i+1} \in [d_{min}, d_{max}] \tag{3}$$

where d is the particle size; d_{min} is the minimum particle size; d_{max} is the maximum particle size; q is the distribution modulus; $P(d)$ is the cumulative fraction of the total solids being smaller than size d; $P_{mix}(d_i^{i+1})$ is the computed cumulative finer fraction of the composed mixture; $P_{target}(d_i^{i+1})$ is the computed cumulative finer fraction of the target function; and RSS is the mathematical representation of the least squares method.

Equation (1) has already been used to improve the particle packing of concrete through three approaches. One approach uses the modified A&A model to design the whole concrete mixture. In this approach, all concrete mixture ingredients (that is, coarse aggregate, fine aggregate, and powders) are proportioned by solving a curve-fitting problem that minimizes the difference between the A&A model and the target function. Several studies have used this approach for proportioning SCC, ultra-high-performance concrete (UHPC), and earth-moist concrete.[10,11,20,30-32] The second approach uses the modified A&A model to optimize the particle packing of fine aggregate. Several studies have used this approach for proportioning UHPC, earth-moist concrete, roller-consolidated concrete (RCC), and SCC.[33-35] The third approach uses the modified A&A model to optimize the PSD of the binder system. A few studies have shown that binary and ternary binder systems with A&A distribution had lower water demand and higher packing density.[36,37]

Although the modified A&A model provides a dense and optimized packing of all granular ingredients, previous studies have not dealt with the best of these three approaches for designing mixtures. In addition, in reviewing the literature, no data was found on the association between the highest packing density and the pumpability of concrete. The next section compares and contrasts the particle packing of the modified A&A model with ACI's empirical data on pumpability.

COMPARISON OF ACI 211.9R-18 WITH MODIFIED A&A MODEL RESULTS

As was pointed out in the previous section, this section compares and contrasts the optimum PSD of the modified

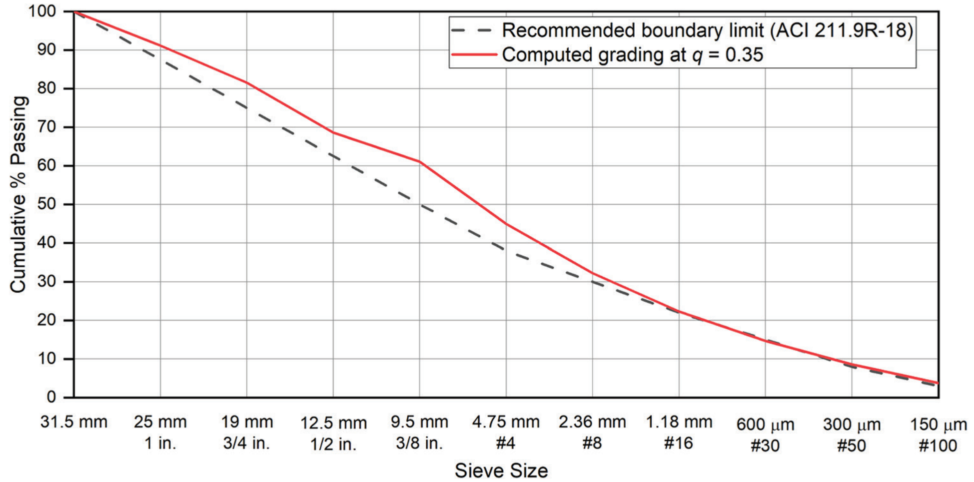

Fig. 1—Computed combined grading of modified A&A model at distribution modulus of 0.35 (represented by solid line) and recommended combined grading for evaluating pumpability of concrete by ACI 211.9R-18 (represented by dashed line).

A&A model with the technical recommendations on the pumpability of concrete by ACI (ACI 211.9R-18).[28] The maximum size of coarse aggregate for proportioning FC mixtures was 31,500 μm, and the minimum size of the powder (for example, cement) was 0.275 μm. In this paper, the term "recommended boundary limit" refers to the recommended combined grading for evaluating the pumpability of concrete by ACI 211.9R-18. According to ACI,[28] a combined aggregate grading above the recommended boundary limit is ideal for pumping. In this paper, the term "computed grading" refers to the computed PSD of the modified A&A model at a specific distribution modulus (q). A considerable amount of literature has been published on the modified A&A model.[10,11,30-40] These studies have used the model at a distribution modulus of 0.35 to 0.2. The paragraphs that follow will compare and contrast these distribution moduli with the ACI's recommendations on pumpability.

Hüsken and Brouwers[31] used the distribution modulus of 0.35 to design earth-moist concrete. They used the modified A&A model to optimize the whole mixture (aggregates and powder), enhance the mixtures' compressive strength, and improve the cement efficiency of zero slump concrete. Khayat and Libre[34] employed the modified A&A model at the distribution modulus of 0.35 to design roller-compacted concrete. They used the model only to optimize aggregates in their mixture.

Figure 1 highlights the difference between the computed grading at $q = 0.35$ and the recommended boundary limit and is quite revealing in several ways. First, the most crucial aspect of the computed grading is that it is identical to the recommended boundary limit for particles smaller than 2.36 mm. Second, it is above the recommended boundary limit for particles larger than 2.36 mm. Taken together, the computed grading at $q = 0.35$ is regarded as ideal for pumping by ACI. That is to say, using the modified A&A model to design the whole concrete mixture (that is, the first approach in previous section) results in an ideal-for-pumping mixture, according to ACI. In contrast, the mixture designs where the model is used only to optimize fine aggregate or the binder system (that is, the second and third approaches in the previous section titled, "Modified A&A Model") do not necessarily lead to ideal-for-pumping mixtures, according to ACI.

Hunger[30] used the modified A&A model to design the whole mixture of SCC. Wang et al.[39] used the modified A&A model at the distribution modulus of 0.29 to optimize the whole mixture (aggregates and powder) and design SCC. Their results showed that this approach could reduce up to 20% binder content compared to existing SCC mixture proportioning methods. Khayat and Mehdipour[33] employed the modified A&A model to optimize aggregates at a distribution modulus of 0.29 to design SCC. Their findings showed that a distribution modulus of 0.29 fits reasonably well to the ideal PSD of aggregates for proportioning SCC with a low binder content.

Figure 2 highlights the difference between the computed grading at $q = 0.3$ and the recommended boundary limit. Compared to Fig. 1, all fractions of the computed grading are above the recommended boundary limit. That is to say, the distribution modulus of 0.30 is considered ideal for pumping. In other words, using the modified A&A model to design the whole concrete mixture (that is, the first approach in the previous section titled, "Modified A&A Model") at a distribution modulus of 0.3 results in an ideal-for-pumping mixture, according to ACI, too.

The better pumpability at a distribution modulus of 0.3 than a higher distribution modulus (for example, at $q = 0.35$) is partly associated with a lower coarse-to-fine aggregate ratio. ACI 211.9R-18 states that the coarse-to-fine aggregate ratio may be modified to improve pumpability but does not state to which degree.[28] This shortcoming is exacerbated when few sources are available for coarse and fine aggregate and powders. In such situations, it is not apparent that the final coarse-to-fine aggregate ratio should be supplied from which aggregates sources. In contrast to the ACI 211.9R-18, in the modified A&A model, the source of the final coarse to fine aggregate ratio can be chosen by solving a curve-fitting problem that minimizes the difference between the A&A model and the target function.[20]

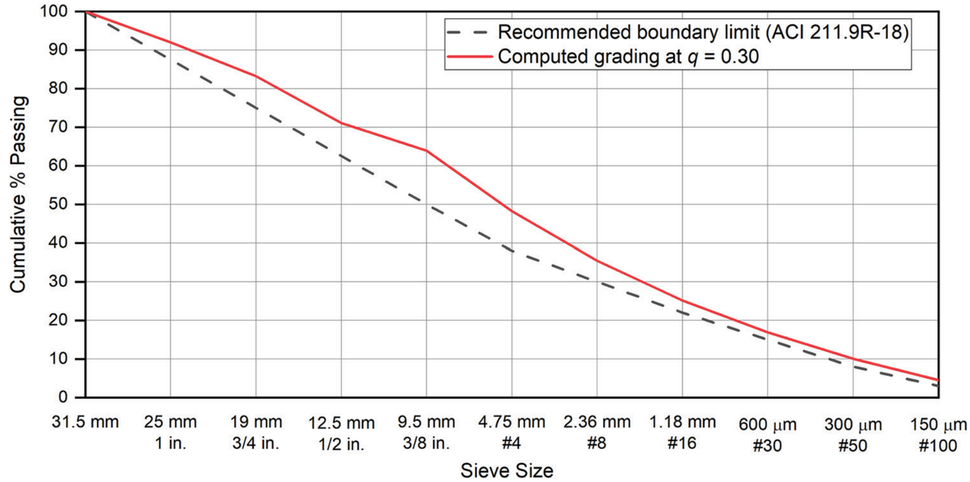

Fig. 2—Computed combined grading of modified A&A model at distribution modulus of 0.30 (represented by solid line) and recommended combined grading for evaluating pumpability of concrete by ACI 211.9R-18 (represented by dashed line).

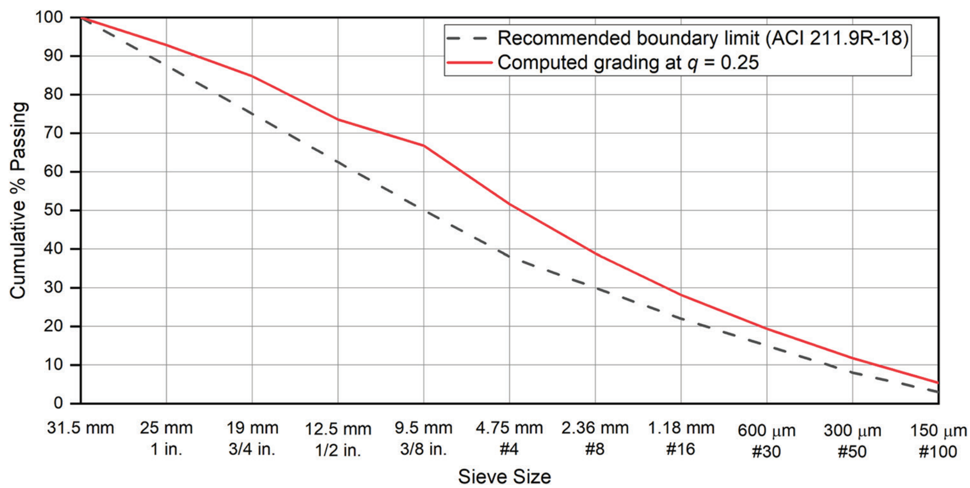

Fig. 3—Computed combined grading of modified A&A model at distribution modulus of 0.25 (represented by solid line) and recommended combined grading for evaluating pumpability of concrete by ACI 211.9R-18 (represented by dashed line).

Mueller et al.[38] used the modified A&A model at a distribution modulus of 0.27 to design SCC. They used the model to optimize the whole mixture (aggregates and powder) and showed that the modified A&A model best describes the PSD of a stable low-powder SCC. Yu et al.[41] developed a cement-based lightweight composite using the modified A&A model at a distribution modulus of 0.25. They used the model to optimize the whole mixture (aggregates and powder) and obtained minor porosity thanks to a more delicate structure, rich in inert fines.

Figure 3 highlights the difference between the computed grading at q = 0.25 and the recommended boundary limit. Compared with Fig. 1 and 2, all fractions of this computed grading are further above the recommended boundary limit. That is to say, the distribution modulus of 0.25 provides a finer particle packing and is ideal for pumping.

The distribution moduli smaller than 0.25 have already been used to develop special concrete mixtures. Yu et al.[40] developed ultra-high-performance fiber-reinforced concrete at a distribution modulus of 0.23. They used the model to optimize the whole mixture (aggregates and powder) and reached a maximum compressive strength of approximately 150 MPa at 28 days. Note that small distribution moduli result in fine mixtures with a low coarse-to-fine ratio. Such mixtures are rich in powders and have higher water demand and shrinkage susceptibility. As a result, they are not suitable for proportioning FC mixtures, although they lead to desirable ultra-high-performance mixtures.

Based on ACI 211.9R-18,[28] experience has shown that for optimum pumpability, 15 to 30% of fine aggregate should be smaller than 300 μm (No. 50 screen), and 5 to 10% should be smaller than 150 μm (No. 100 screen). This recommendation needs further clarification. Although the smaller particles lubricate the larger ones, a large difference exists between a mixture containing 30% fine aggregate smaller than 300 μm and one containing only 15%. ACI 211.9R-18 also advises blending fine aggregate deficient in either of these two sizes with fine sand, which needs further clarification, too.[28] Adding another sand will not only modify the percentage of fine aggregate smaller than 300 μm, but also change the percentage of fine aggregate larger than 300 μm. What remains unclear in ACI recommendations is how and to what degree these modifications need to be implemented. By contrast, the most prominent finding to emerge from the

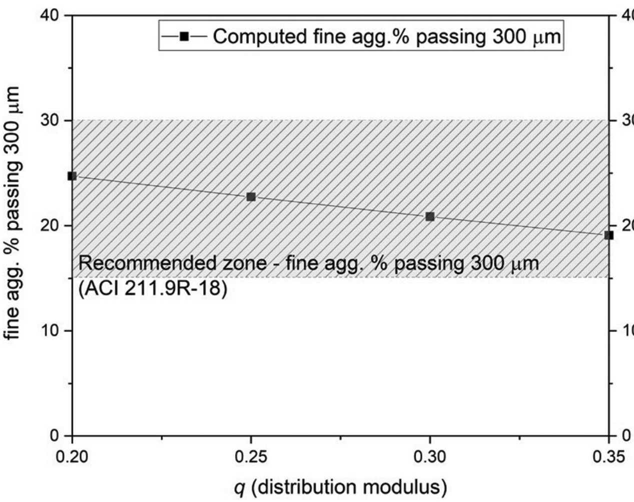

Fig. 4—Recommended percentage of fine aggregate passing 300 μm (No. 50 screen) (represented by cross-hatched area) and computed fine aggregate of modified A&A model at distribution moduli of 0.20 to 0.35.

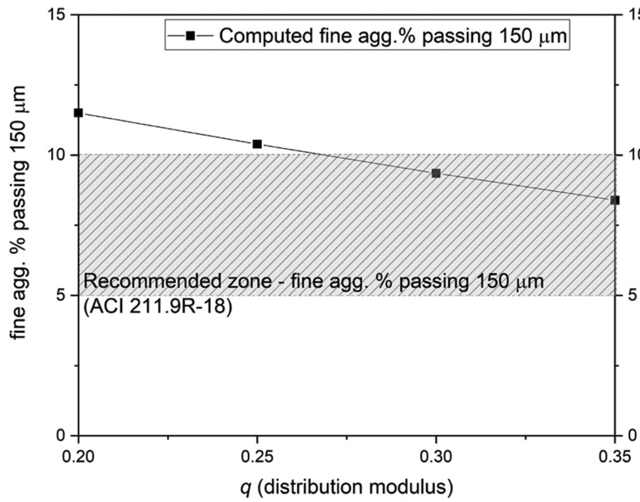

Fig. 5—Recommended percentage of fine aggregate passing 150 μm (No. 100 screen) (represented by cross-hatched area) and computed fine aggregate of modified A&A model at distribution moduli of 0.20 to 0.35.

Table 1—Chemical composition of CEM I 52.5 R and CEM III 42.5 LH/SR, measured by XRF (in weight percent)

	MgO	Al_2O_3	SiO_2	SO_3	CaO	Fe_2O_3	LOI
CEM I	1.6	6.2	17.7	3.0	64.7	3.5	2.5
CEM III	4.6	9.5	28.2	5.1	49.8	1.3	0.3

Note: LOI is loss on ignition.

modified A&A model is the percentage of fine aggregate smaller than 300 μm and how each blended fine aggregate contributes to removing the deficiency in particles finer than 300 μm. This point is discussed in more detail as follows.

Figures 4 and 5 compare ACI's recommended percentage of fine aggregate passing 300 μm (No. 50 screen) and 150 μm (No. 100 screen) with the computed fine aggregate in modified A&A model at q = 0.35 to 0.20. The computed fine aggregate passing 300 μm is approximately 20% at q = 0.35 and increases to 25% at q = 0.20. The computed fine aggregate passing 150 μm is just above 8% at q = 0.35 and rises to 11.5% at q = 0.20. What stands out in these figures is the high degree to which the modified A&A model is compatible with the ACI recommendations. The adjustments in the distribution modulus of the modified A&A model make it possible to design mixtures with high packing density at various coarse-to-fine aggregate ratios. As discussed earlier in this section, this feature along with the choice of the maximum and minimum size of aggregates make this method suitable for designing various types of concrete.

The findings of this section provided a deeper insight into the pumpability of the modified A&A model. When this model is used to design the whole mixture (aggregates and powders), it is highly compatible with the technical recommendations on the pumpability of concrete by ACI 211.9R-18. The modified A&A model at a distribution modulus of 0.35 is the boundary limit for ideal pumpability. A distribution modulus smaller than 0.35 is considered ideal for pumping. The choice of distribution modulus depends on the application for which the concrete mixture is designed. The theoretical background of the modified A&A model makes it possible to optimize pumpability for various applications.

EXPERIMENTAL INVESTIGATION

Materials

The current investigation involved the production and analysis of flowing concrete. CEM I 52.5R[42] and CEM III 42.5 LH/SR[43] cements were used to produce concretes. The CEM I 52.5R was fine portland cement (Blaine of approximately 527 m^2/kg), with an initial setting time of 111 minutes (EN 196-3), final setting time of 159 minutes (EN 196-3), and a median particle size of 14 μm. The CEM III/B 42.5 LH/SR was a fine binary blend of slag and portland clinker (Blaine of approximately 488 m^2/kg), with an initial setting time of 224 minutes (EN 196-3), final setting time of 264 minutes (EN 196-3), and a median particle size of 16 μm. The chemical composition of both cement types was determined by X-ray fluorescence (XRF) and is shown in Table 1.

River gravel with a maximum size of aggregate (MSA) of 31.5 mm and river sand were used to produce concrete. A polycarboxylic ether-based HRWRA with a solid content of 12% was used to adjust the flow properties of flowing concretes. The dosage of the HRWRA refers to the weight of the solution in water as a percentage of the weight of cement. The water in the HRWRA solution was deducted from the mixing water. The powders' PSD was measured employing a particle size analyzer, and sieve analysis was used to measure the PSD of the aggregates. The PSD of the solid ingredients of the concretes at a distribution modulus

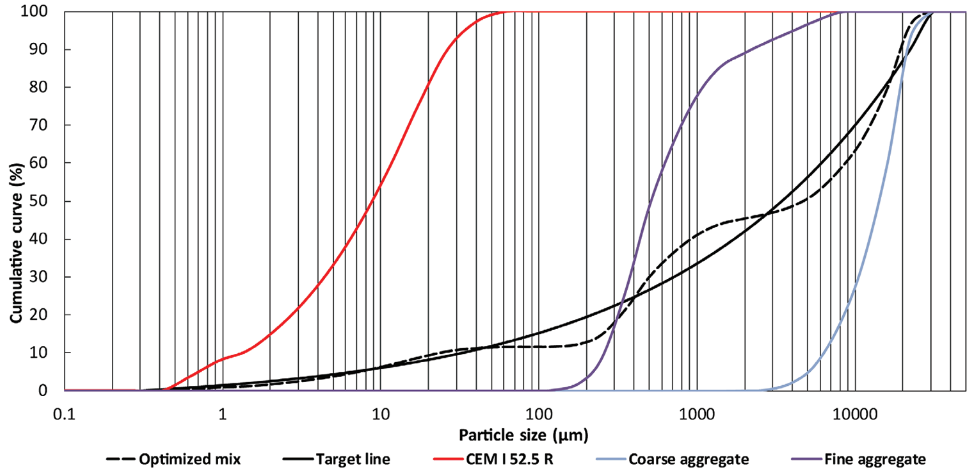

Fig. 6—Particle-size distribution of different ingredients of flowing concrete containing CEM I. Target line was computed by modified A&A model at distribution modulus of 0.3. Optimized mixture is best fit of ingredients for target line (R^2 *= 0.976).*

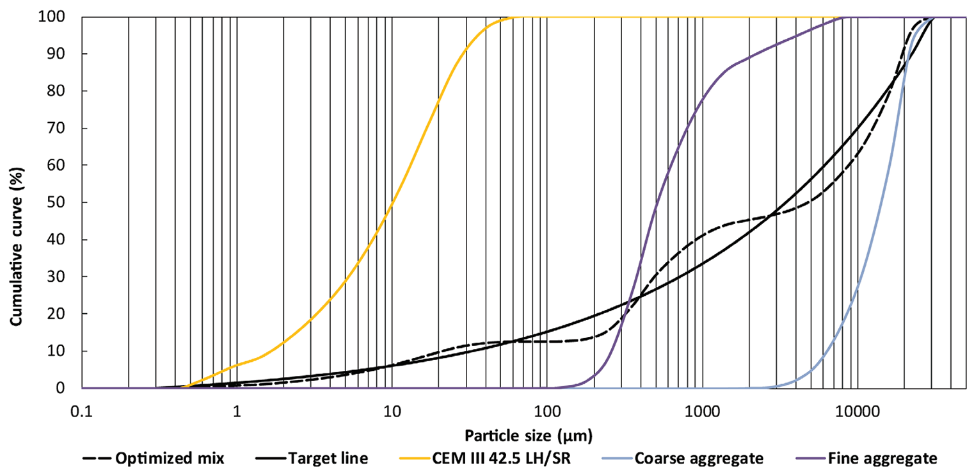

Fig. 7—Particle-size distribution of different ingredients of flowing concrete containing CEM III. Target line was computed by modified A&A model at distribution modulus of 0.3. Optimized mixture is best fit of ingredients for target line (R^2 *= 0.977).*

of 0.3 is shown in Fig. 6 and 7. The mixtures are explained in more detail in the next section.

Mixing

A standard pan mixer with planetary motion blades was used for producing flowing concretes. First, cement and sand were blended in a dry state for 1 minute. Then, approximately 75% of the mixing water was added while further mixing for 90 seconds. Afterward, a solution of the HRWRA and the remaining water was added and mixed for 1 minute. Finally, the coarse aggregate were added and mixed for another 2 minutes. HRWRA was added at the end of the mixing sequence to prevent possible competing of HRWRA molecules with calcium sulfate present in the cement to combine with C_3A.[44] It ensured that all the HRWRA molecules were kept ready to make concrete more flowable.[44]

Testing methods

The flow table test was used to analyze the fresh properties of flowing concretes according to EN 12350-5.[16] First, the flow table was cleaned and damped with a moist cloth. Next, the mold was filled with concrete in two layers, where each layer was tamped 10 times. After waiting for 30 seconds, the mod was raised over a period of 1 to 3 seconds. Then, the flow was checked for segregation and bleeding. The consistency was the average of maximum dimensions of concrete spread, in two directions parallel to the table edges, measured to the nearest 10 mm. After mixing, concrete was placed into six cube molds (150 x 150 x 150 mm) and covered by a plastic film to prevent moisture loss. The samples were unmolded approximately 24 hours after casting and then submerged in water at 20°C for curing. The compressive strength tests were performed after 28 and 98 days, according to EN 12390-3 (rate of loading: 0.6 ± 0.2 MPa/s).[45]

Furthermore, concrete was placed into three prism molds (100 x 100 x 200 mm) to measure free drying shrinkage and report their average result. The specimens were unmolded 24 hours after casting to install vibrating wire strain gauges. The specimens were dried in a climate chamber at 20°C and 60% relative humidity. The vibrating wire strain gauges work with the principle of an electric guitar. They are composed of two end pieces joined by a tube that protects a length of steel wire. An electromagnet is placed in a protective housing located at the center of the tube. The exterior forces applied on the strain gauge modify the tension in the

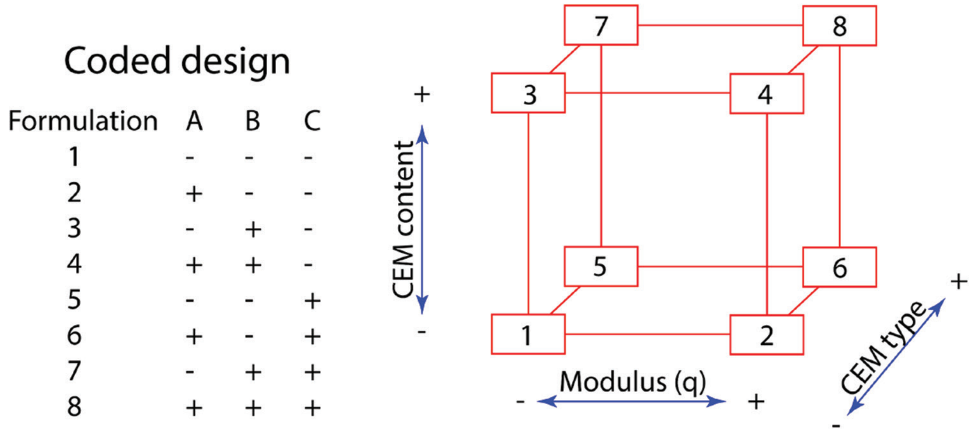

Fig. 8—A 2^3 factorial experimental design: (left) coded design in standard order; and (right) cube plot of numbered runs used to study influence of three factors.

wire and the wire's resonant frequency, which is read by the electromagnet.

The vibrating wire readings were drying shrinkage because, in concrete having a water-cement ratio (*w*/*c*) greater than 0.45, the autogenous shrinkage is negligible compared to drying shrinkage.[46,47] This insignificance is thanks to two factors: 1) excess water more than required for full hydration of cement; and 2) large, well-connected capillary pores.[46,47]

Mixtures

A factorial design was employed at two levels with three factors, including two quantitative factors and a single qualitative factor:

1. Distribution modulus of the modified A&A model (q = 0.35, q = 0.3);

2. Cement content (300 and 260 kg/m^3); and

3. Cement type (CEM I 52.5R and CEM III 42.5 LH/SR).

The choice of distribution moduli (q = 0.35, q = 0.3) was based on previous tests performed by the authors and the scientific literature discussed previously. The choice of the cement content was based on EN 206,[17] where:

1. The minimum cement content for the exposure class of XC 1 (Level 1 carbonation-induced corrosion) is stated as 260 kg/m^3; and

2. The minimum cement content for the exposure classes of XS 1 and XD 1 (Level 1 chloride-induced corrosion due to seawater and chloride other than seawater), XF 1 (Level 1 freeze/thaw attack), and XA 1 (Level 1 aggressive chemical environments) is stated as 300 kg/m^3.

The choice of cement type was based on their widespread use in the manufacture of concrete floors in different seasons of the year. The CEM I 52.5R cement has a rapid hydration rate and is usually used for concreting in winter, while the CEM III 42.5 LH/SR cement has a low hydration rate and is usually used for concreting in summer.[42,43] A higher dosage of HRWRA was used in samples with 260 kg/m^3. The water content in these samples was only 130 kg/m^3 (compared to 150 kg/m^3 water in samples with 300 kg/m^3 cement), and the higher HRWRA dosage helped to improve flowability.

In this study, a 2^3 factorial experimental design was used to investigate the variables. The coded design consisted of eight formulations, as shown in the table on the left of Fig. 8. Each data value was for the response yield averaged over three duplicate measurements. For example, a run using the lower amount of distribution modulus (q = 0.35), the lower content of cement (260 kg/m^3), and the CEM I was coded as (– – –) or run 1. As shown in Fig. 8, these eight formulations can be represented by the vertexes of a cube. If the cube center is considered the origin of a three-dimensional coordinate system, then the factors can be identified by the coordinates of these points.[48]

Furthermore, a Pareto analysis at a 5% significance level was performed to determine which effects (main and interaction) contribute the most to the consistency and shrinkage response variability. The main effects were: (A) modulus; (B) cement content; and (C) cement type. The interaction terms were AB, AC, and BC.

EXPERIMENTAL RESULTS AND DISCUSSION

Consistency

Figure 9(a) presents the consistency of mixtures, measured by flow table test for the eight combinations of factors at the corners of a cube. No indication of segregation was observed during measurements. The Pareto analysis showed that among the factors, the cement content was the most statistically significant factor to the consistency response variability (adjusted R^2 = 98.5% and predicted R^2 = 86.3%). The analysis also showed that none of the interaction terms were statistically significant (α = 5%). In other words, both distribution moduli (q = 0.35 and 0.30) produced workable, cohesive, flowing concrete, and distribution modulus was not a statistically significant factor to the consistency response variability.

Figure 9(b) shows the influence of distribution modulus on the consistency of mixtures. The average main effect of distribution modulus on flow diameter is +3 cm, which is greater at lower cement content. At 300 kg/m^3, both distribution moduli (q = 0.35 and 0.30) provided cohesive, workable, flowing concrete. No indication of segregation and bleeding was found in the samples. Figure 9(c) displays the influence of the cement content and HRWRA dosage on the consistency of mixtures. The average main effect of cement content is +7 cm, which is more than twofold that of the

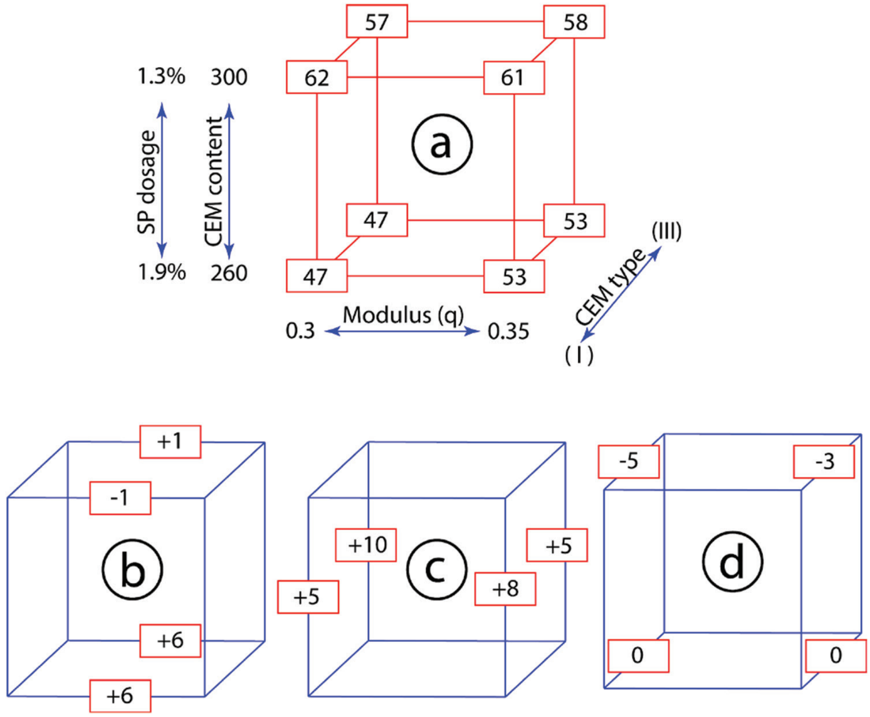

Fig. 9—(a) Cube plot of consistency of mixtures (cm), measured by flow table test; and influence of factors on flow diameter: (b) influence of distribution modulus; (c) influence of cement content and HRWRA dosage; and (d) influence of cement type.

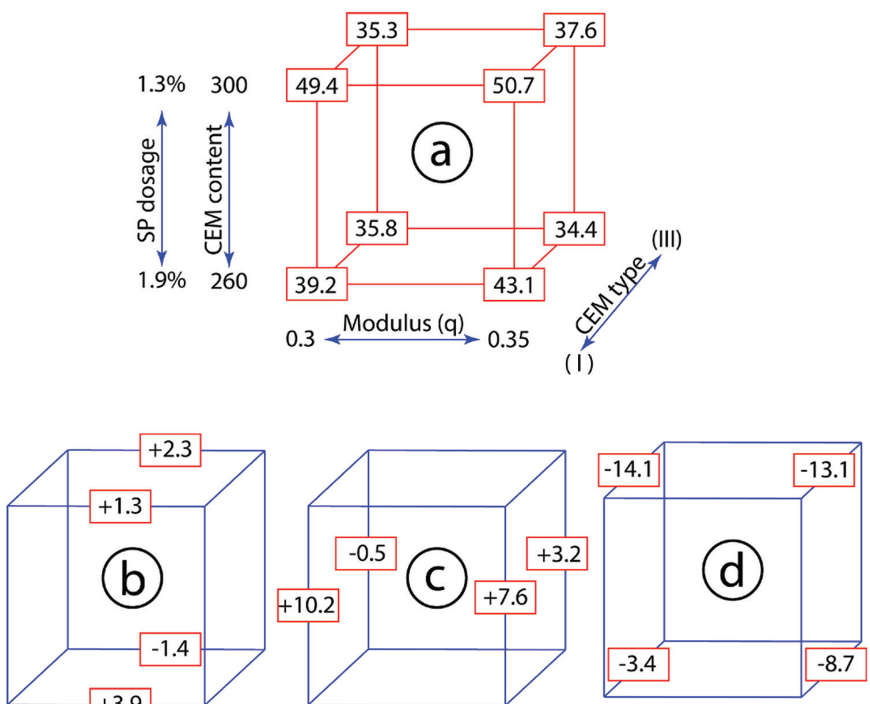

Fig. 10—(a) Cube plot of 28-day strength (MPa); and (bottom) influence of factors on 28-day strength: (b) influence of distribution modulus; (c) influence of cement content and HRWRA dosage; and (d) influence of cement type.

distribution modulus. In similar mixtures, a higher amount of powder is translatable into a higher volume of excess paste. Figure 9(d) shows the influence of cement type on the consistency of mixtures. The average main effect of cement type is −2 cm, which is greater at higher cement content. This effect is insignificant as it is less than the tolerance of flow diameter test (±30 mm), according to EN 206-1.[17]

Compressive strength

Figure 10(a) presents the 28-day strength of mixtures for the eight combinations of factors at the corners of a cube. Figure 10(b) shows the influence of distribution modulus on the 28-day strength of mixtures. The strength of all the CEM I mixtures is above 37 MPa, which is the minimum cube strength for C30/37 compressive strength class in EN

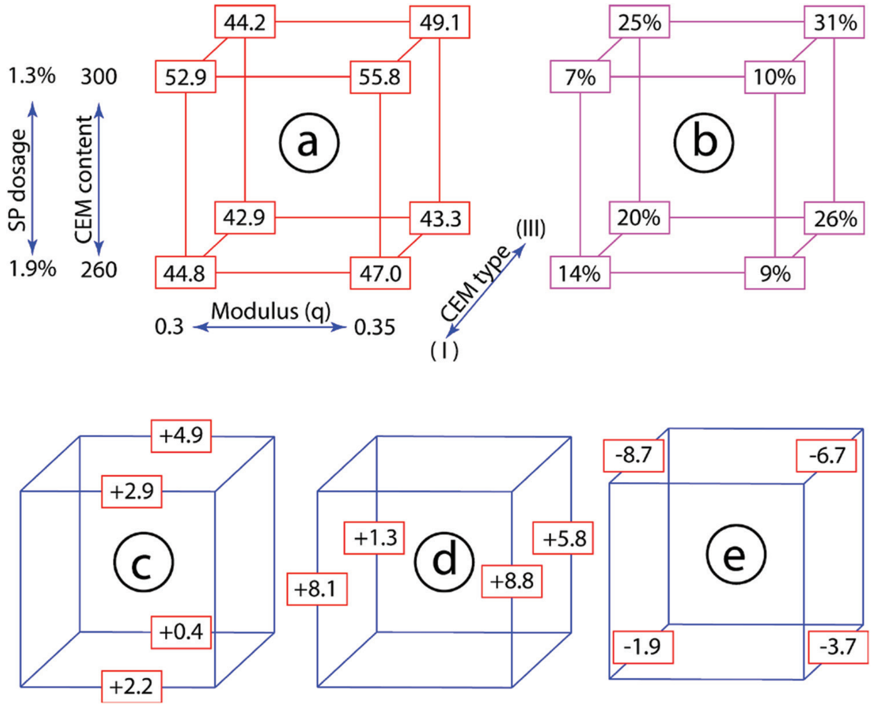

Fig. 11—(a) Cube plot of 98-day strength (MPa); (b) percentage increase in strength compared to 28-day strength; and influence of factors on 98-day strength: (c) influence of distribution modulus; (d) influence of cement content and HRWRA dosage; and (e) influence of cement type.

206-1.[17] The average main effect of the distribution modulus on the 28-day strength is +1.5 MPa, showing the two distribution moduli provide similar strength. Figures 10(c) and (d) display the influence of cement content and type on the 28-day strength of mixtures. Mixtures containing CEM III have lower compressive strength due to the lower hydration speed of CEM III.[43]

Figure 11(a) presents the 98-day strength of mixtures for the eight combinations of factors at the corners of a cube. Compared to the 28-day strength of the mixtures (Fig. 10), the increase in 98-day strength is more significant in CEM III mixtures. Rapid strength gain in CEM I mixtures is associated with the high surface area of this type of cement (Blaine of ~527 m^2/kg). Figure 11(c) shows the influence of the distribution modulus on the 98-day strength of mixtures. The strength of the mixtures is above 43 MPa, which is considered sufficient for most flowing concrete applications. The average main effect of distribution modulus on the 98-day strength is +2.6 MPa, and the two distribution moduli provide similar adequate strength. Figure 11(d) demonstrates the influence of cement content on the 98-day strength of mixtures. The average main effect of cement content is +6 MPa, and a higher cement content results in higher strength. Figure 11(e) shows the influence of cement type on the 28-day strength of mixtures. Mixtures containing CEM III have lower compressive strength due to the lower hydration speed of CEM III.[43]

Drying shrinkage

Figure 12(a) presents the 98-day drying shrinkage of the eight combinations of factors at the corners of a cube. The Pareto analysis showed that among the factors, the distribution modulus was the most statistically significant factor to the 98-day shrinkage response variability (adjusted R^2 = 96.4% and predicted R^2 = 67.3%). The analysis also showed that none of the interaction terms were statistically insignificant (α = 5%).

The shrinkage values are less than 380 με (μm/m), showing that the mixture design method can make low-shrinkage, flowing concrete mixtures. Figure 12(b) illustrates the influence of distribution modulus on the drying shrinkage of mixtures. Its average main effect is +33.5 με and is associated with a higher coarse-to-fine ratio. Figure 12(c) shows the influence of cement content on the drying shrinkage of mixtures. Its average main effect is +5.5 με, which is due to the difference in the water content of the mixtures (refer to Table 2). Figure 12(d) shows the influence of cement type on the drying shrinkage of mixtures. The lesser shrinkage in CEM III samples may be attributed to the lower hydration speed in this type of cement.[43] These results are in line with previous studies where 60% volume replacement of cement with slag exhibited 22% and 12% lower drying shrinkage at 30 days and 356 days, respectively.[49]

CONCLUSIONS

In the present paper, the pumpability of the modified Andreasen and Andersen (A&A) model at a distribution modulus of 0.35 to 0.2 was compared and contrasted with the technical literature and the recommendations of the American Concrete Institute (ACI). A factorial design was used to investigate the consistency, compressive strength, and drying shrinkage of flowing concrete mixtures. Based on the properties assessed and the results obtained, the following conclusions can be drawn:

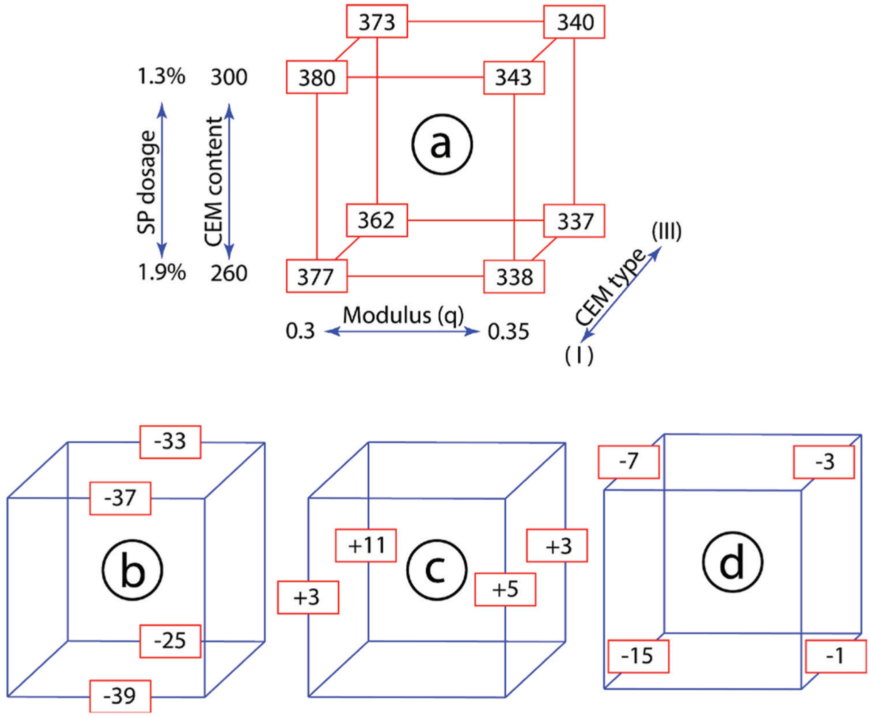

Fig. 12—(a) Cube plot of 98-day shrinkage (με, μm/m); and influence of factors on 98-day shrinkage: (b) influence of distribution modulus; (c) influence of cement content and HRWRA dosage; and (d) influence of cement type.

Table 2—Concrete mixture compositions at *w/c* of 0.50

Designation	Distribution modulus *q*	Cement type	Cement, kg/m^3	Sand, kg/m^3	Gravel, kg/m^3	Water, kg/m^3	HRWRA, %
C1	0.30	CEM I	260	912.0	1142.4	130	1.9%
C2	0.35	CEM I	260	780.0	1274.4	130	1.9%
C3	0.30	CEM I	300	843.1	1123.3	150	1.3%
C4	0.35	CEM I	300	714.2	1252.2	150	1.3%
C5	0.30	CEM III	260	888.6	1146.2	130	1.9%
C6	0.35	CEM III	260	756.6	1278.2	130	1.9%
C7	0.30	CEM III	300	816.1	1127.7	150	1.3%
C8	0.35	CEM III	300	687.2	1256.6	150	1.3%

- The modified A&A model optimizes the particle size distribution of concrete to produce pumpable concretes according to ACI 211.9R-18. The distribution modulus of the model controls the combined grading, the ratio of coarse-to-fine aggregate, and the percentage of fine aggregate passing 300 and 150 μm.
- When designing concrete with the modified A&A model, a distribution modulus of 0.35 is the recommended boundary limit for ideal pumpability, according to ACI 211.9R-18. A distribution modulus smaller than 0.35 results in ideal-for-pumping mixtures, according to ACI 211.9R-18.
- When designing concrete with the modified A&A model, the lowering of the distribution modulus pushes the cumulated combined grading further above the recommended boundary limit for ideal pumpability. It also increases the percentage of fine aggregate passing 300 and 150 μm while keeping them within the limits recommended by ACI 211.9R-18.
- A good correlation was established between the distribution modulus of the modified A&A model and the drying shrinkage of concrete. A high distribution modulus in the model results in a high coarse-to-fine aggregate ratio and lowers the drying shrinkage of concrete.

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REFERENCES

1. Mehta, P. K., and Monteiro, P. J. M., *Concrete—Microstructure, Properties, and Materials*, third edition, McGraw-Hill, New York, 2006, 659 pp.

2. Neville, A. M., and Brooks, J. J., *Concrete Technology*, second edition, Prentice Hall, Upper Saddle River, NJ, 2010, 442 pp.

3. Kosmatka, S. H.; Kerkhoff, B.; and Panarese, W. C., *Design and Control of Concrete Mixtures*, fifth edition, Portland Cement Association, Skokie, IL, 2011, 411 pp.

4. ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) (Reapproved 2009)," American Concrete Institute, Farmington Hills, MI, 2009, 38 pp.

5. ACI Committee 309, "Guide for Consolidation of Concrete (ACI 309R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 36 pp.

6. ACI Committee 237, "Self-Consolidating Concrete (ACI 237R-07)," American Concrete Institute, Farmington Hills, MI, 2007, 30 pp.

7. Khayat, K. H., and de Schutter, G., eds., *Mechanical Properties of Self-Compacting Concrete*, Springer, Dordrecht, the Netherlands, 2014, 271 pp.

8. Khayat, K. H., and Feys, D., eds., *Design, Production and Placement of Self-Consolidating Concrete*, Springer, Dordrecht, the Netherlands, 2010, 458 pp.

9. Yahia, A., and Aïtcin, P.-C., "Self-Consolidating Concrete," *Science and Technology of Concrete Admixtures*, P.-C. Aïtcin and R. J. Flatt, eds., Woodhead Publishing, Sawston, UK, 2015, pp. 491-502.

10. Brouwers, H. J. H., and Radix, H. J., "Self-Compacting Concrete: Theoretical and Experimental Study," *Cement and Concrete Research*, V. 35, No. 11, 2005, pp. 2116-2136. doi: 10.1016/j.cemconres.2005.06.002

11. Brouwers, H. J. H., and Radix, H. J., "Self-Compacting Concrete: The Role of the Particle Size Distribution," *SCC'2005-China - 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete*, Changsha, Hunan, China, 2005. pp. 109-118.

12. Schmidt, W.; Brouwers, H. J. H.; Kühne, H. C.; and Meng, B., "The Working Mechanism of Starch and Diutan Gum in Cementitious and Limestone Dispersions in Presence of Polycarboxylate Ether Superplasticizers," *Applied Rheology (Lappersdorf, Germany)*, V. 23, No. 5, 2013

13. TR 34, "Concrete Industrial Ground Floors — A Guide to Design and Construction," fourth edition, The Concrete Society, Surrey, UK, 2013, 91 pp.

14. ACI, "ACI Concrete Terminology (CT-18)," American Concrete Institute, Farmington Hills, MI, 2018, 80 pp.

15. ASTM C1017/C1017M-13e1, "Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete," ASTM International, West Conshohocken, PA, 2017, 9 pp.

16. BS EN 12350-5:2009, "Testing Fresh Concrete — Flow Table Test," British Standards Institution, London, UK, 2009, 14 pp.

17. BS EN 206:2013+A1:2016, "Concrete, Specification, Performance, Production and Conformity," British Standards Institution, London, UK, 2016, 106 pp.

18. Alexander, M. G., and Mindess, S., *Aggregates in Concrete*, first edition, CRC Press, London, UK, 2005, 448 pp.

19. Roussel, N., *Understanding the Rheology of Concrete*, Woodhead Publishing, Sawston, UK, 2012, 373 pp.

20. Hüsken, G., "A Multifunctional Design Approach for Sustainable Concrete: With Application to Concrete Mass Products," PhD thesis, Eindhoven University of Technology, Eindhoven, the Netherlands, 2010, 243 pp.

21. de Larrard, F., *Concrete Mixture Proportioning—A Scientific Approach*, E & FN Spon, London, UK, 1999, 421 pp.

22. Goltermann, P.; Johansen, V.; and Palbøl, L., "Packing of Aggregates: An Alternative Tool to Determine the Optimal Aggregate Mix," *ACI Materials Journal*, V. 94, No. 5, Sept.-Oct. 1997, pp. 435-443.

23. Jones, M. R.; Zheng, L.; and Newlands, M. D., "Comparison of Particle Packing Models for Proportioning Concrete Constitutents for Minimum Voids Ratio," *Materials and Structures*, V. 35, No. 5, 2002, pp. 301-309. doi: 10.1007/BF02482136

24. Hendrix, G., and Trejo, D., "New Mixture Proportioning Method for Flowing Concrete Mixtures," *ACI Materials Journal*, V. 114, No. 4, July-Aug. 2017, pp. 507-516. doi: 10.14359/51689894

25. Su, N., and Miao, B., "A New Method for the Mix Design of Medium Strength Flowing Concrete with Low Cement Content," *Cement and Concrete Composites*, V. 25, No. 2, 2003, pp. 215-222. doi: 10.1016/S0958-9465(02)00013-6

26. Fataei, S.; Secrieru, E.; Mechtcherine, V.; and Roussel, N., "A First-Order Physical Model for the Prediction of Shear-Induced Particle Migration and Lubricating Layer Formation during Concrete Pumping," *Cement and Concrete Research*, V. 147, 2021, p. 106530. doi: 10.1016/j.cemconres.2021.106530

27. Choi, M.; Roussel, N.; Kim, Y.; and Kim, J., "Lubrication Layer Properties during Concrete Pumping," *Cement and Concrete Research*, V. 45, 2013, pp. 69-78. doi: 10.1016/j.cemconres.2012.11.001

28. ACI Committee 211, "Guide to Selecting Proportions for Pumpable Concrete (ACI 211.9R-18)," American Concrete Institute, Farmington Hills, MI, 2018, 51 pp.

29. Andreasen, A. H. M., and Andersen, J., "Ueber die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten)," *Kolloid-Zeitschrift*, V. 50, 1930, pp. 217-228. (in German) doi: 10.1007/BF01422986

30. Hunger, M., "An Integral Design Concept for Ecological Self-Compacting Concrete," PhD thesis, Eindhoven University of Technology, Eindhoven, the Netherlands, 2010, 240 pp.

31. Hüsken, G., and Brouwers, H. J. H., "A New Mix Design Concept for Earth-Moist Concrete: A Theoretical and Experimental Study," *Cement and Concrete Research*, V. 38, No. 10, 2008, pp. 1246-1259. doi: 10.1016/j.cemconres.2008.04.002

32. Yu, R.; Spiesz, P.; and Brouwers, H. J. H., "Development of an Eco-Friendly Ultra-High-Performance Concrete (UHPC) with Efficient Cement and Mineral Admixtures Uses," *Cement and Concrete Composites*, V. 55, 2015, pp. 383-394. doi: 10.1016/j.cemconcomp.2014.09.024

33. Khayat, K. H., and Mehdipour, I., "Design and Performance of Crack-Free Environmentally Friendly Concrete 'Crack-Free Eco-Crete,'" Report NUTC R322, 2014, 145 pp.

34. Khayat, K. H., and Libre, N., "Roller Compacted Concrete: Field Evaluation and Mixture Optimization," Rep. NUTC R363, 2014, 118 pp.

35. Meng, W.; Valipour, M.; and Khayat, K. H., "Optimization and Performance of Cost-Effective Ultra-High-Performance Concrete," *Materials and Structures*, V. 50, No. 29, 2016, pp. 1-16.

36. Mehdipour, I., and Khayat, K. H., "Understanding the Role of Particle Packing Characteristics in Rheo-Physical Properties of Cementitious Suspensions: A Literature Review," *Construction and Building Materials*, V. 161, 2018, pp. 340-353. doi: 10.1016/j.conbuildmat.2017.11.147

37. Mehdipour, I., and Khayat, K. H., "Effect of Particle-Size Distribution and Specific Surface Area of Different Binder Systems on Packing Density and Flow Characteristics of Cement Paste," *Cement and Concrete Composites*, V. 78, 2017, pp. 120-131. doi: 10.1016/j.cemconcomp.2017.01.005

38. Mueller, F. V.; Wallevik, O. H.; and Khayat, K. H., "Linking Solid Particle Packing of Eco-SCC to Material Performance," *Cement and Concrete Composites*, V. 54, 2014, pp. 117-125. doi: 10.1016/j.cemconcomp.2014.04.001

39. Wang, X.; Wang, K.; Taylor, P.; and Morcous, G., "Assessing Particle Packing Based Self-Consolidating Concrete Mix Design Method," *Construction and Building Materials*, V. 70, 2014, pp. 439-452. doi: 10.1016/j.conbuildmat.2014.08.002

40. Yu, R.; Spiesz, P.; and Brouwers, H. J. H., "Mix Design and Properties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)," *Cement and Concrete Research*, V. 56, 2014, pp. 29-39. doi: 10.1016/j.cemconres.2013.11.002

41. Yu, Q. L.; Spiesz, P.; and Brouwers, H. J. H., "Development of Cement-Based Lightweight Composites – Part 1: Mix Design Methodology and Hardened Properties," *Cement and Concrete Composites*, V. 44, 2013, pp. 17-29. doi: 10.1016/j.cemconcomp.2013.03.030

42. ENCI, "Portland Cement, CEM I 52,5 R, Technical Advice," 's-Hertogenbosch, the Netherlands, 2017, 2 pp.

43. ENCI, "Portland Cement, CEM III/B 42,5 L-LH/SR, Technical Advice," 's-Hertogenbosch, the Netherlands, 2020, 5 pp.

44. Aïtcin, P.-C., *High Performance Concrete*, E & FN Spon, New York, 1998, 591 pp.

45. BS EN 12390-3:2009, "Testing Hardened Concrete. Compressive Strength of Test Specimens," British Standards Institution, London, UK, 2009, 22 pp.

46. Aïtcin, P.-C., "Demystifying Autogenous Shrinkage," *Concrete International*, V. 21, No. 11, Nov. 1999, pp. 54-56.

47. Aïtcin, P.-C., "The Durability Characteristics of High-Performance Concrete: A Review," *Cement and Concrete Composites*, V. 25, No. 4-5, 2003, pp. 409-420. doi: 10.1016/S0958-9465(02)00081-1

48. Box, G. E. P.; Hunter, J. S.; and Hunter, W. G., *Statistics for Experimenters: Design, Innovation, and Discovery*, Wiley, 2005, 664 pp.

49. Yuan, J.; Lindquist, W.; Darwin, D.; and Browning, J. N., "Effect of Slag Cement on Drying Shrinkage of Concrete," *ACI Materials Journal*, V. 112, No. 2, Mar.-Apr. 2015, pp. 267-276. doi: 10.14359/51687129

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