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Mixture-proportioning of high-performance concrete

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Abstract

The paper presents a new approach to design concrete mixtures. It is based upon a set of models relating composition and engineering properties of concrete, to be implemented into software, linked with a material database. The principles underlying the various models are summarized, most of which focus on the granular structure of fresh/hardened concrete. A global approach to concrete is promoted, where performance specifications can be formulated in terms of fresh concrete (yield stress, plastic viscosity, slump and air content), hardening concrete (adiabatic temperature rise and autogenous shrinkage) and hardened concrete (compressive strength at any age, tensile strength, elastic modulus, creep and shrinkage). This approach is illustrated through the design of a special high-shrinkage high-performance concrete (HPC) for road application. To date, durability is lacking in the model and requires further research.

Keywords: Mixture-proportioning; Rheology; Mechanical properties; Shrinkage; Software

1. Introduction

In the recent years, the concrete mixture-proportioning problem has become more and more complicated. First, new components appeared, like organic admixtures, supplementary cementitious materials (as fly ash, filler, etc.) and fibres. Second, emphasis was put on a growing number of concrete properties, dealing with the whole life cycle (from fresh state rheological behavior to durability in various environments). Third, the range of attainable properties displayed a dramatic increase. Restricting ourselves to the aspects most commonly considered in mix-design, dry to ultra-fluid (self-compacting) mixtures are available nowadays. Likewise, compressive strength from 1–2 MPa (for re-excavable controlled low-strength materials) to 200 MPa (for ultra-high strength mortars used, e.g., in containers devoted to radioactive waste materials) can be envisaged. To summarize, the mix-design problem involves more variables and more dimensions in a larger space than before (mathematically speaking).

Appearance of high-performance concrete (HPC) is another recent phenomenon. In Europe, HPC is considered to be a concrete having a high strength at 28 days (typically > 60 MPa in compressive strength) or a low water–binder ratio (< 0.40). In USA, HPC is supposed to be a special mixture, matching specific requirements that cannot be achieved on a routine basis. Finally, what is needed everywhere is 'à la carte' concrete, that is, a mixture that matches a comprehensive list of requirements, by using local materials at minimum cost. This is the problem investigated in the present paper.

Facing this reality, which is no more than the normal progress of concrete technology, the formulator is submitted to growing time and cost constraints. For instance, it is not seldom seeing a concrete study starting < 28 days before the beginning of a construction site, which means that the actual compressive strength is unknown while the first concrete is cast into the structure. Moreover, the concrete market is very competitive in Europe. It turns out that concrete companies have only restricted budgets to spend in mix-design, although from this fundamental stage comes a great deal of consequences for the site operations and for the structure to be built.

Based upon these considerations, LCPC decided to develop concrete mixture-proportioning software. A first product, entitled Bétonlab [1,2] and proposed in 1992,

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was created for tutorial purposes. A sort of 'electronic laboratory' was given to the user, in order to allow him to 'cast concrete on his desk.' Emphasis was put on the ease of utilization. After having filled up a small number of boxes dealing with the constituents, one could simulate the production of laboratory trial batches. The advantage was to immediately obtain the test results, with the drawback of limited precision of the simulations. But the aim was to provide the user with an understanding of the system behavior, so that he could efficiently react in a real situation. This product has been widely distributed in France (about 300 copies), and remains a suitable tool, especially for training students or professionals.

Out of France, other mix-design software programs were proposed. A comprehensive review of this matter was recently published by Polish researchers [3]. Some products are essentially a programming of conventional mix-design methods like the ACI method or the French Dreux's method. Other programs deal with an original approach, as Day's one (more devoted to quality control than to initial mixture-proportioning) or Dewar's method, based upon a ternary packing model. However, among these methods few of them are based on a sound and explicit scientific approach.

Given the recent advances in computer technology, the practical use of numerical models is no longer difficult. Assembling models to use them together can be readily performed with a common spreadsheet package. What remains difficult and challenging is the construction of the models themselves, which must express the relationship between mix-composition and engineering properties as precisely as possible. This is why LCPC started such a research effort some years ago. A number of doctoral theses were prepared with complementary objectives. Together with other works, they are summarized in a recent book [4]. An overview of this scientific basis is given in the present paper, together with a selection of most significant figures. Then a practical example is presented, dealing with the design of a special HPC for pavement application.

2. Overall approach

In most of the models developed, emphasis is put on the granular structure of concrete. First, the packing density and segregation ability of dry packing of particles are studied. Second, attention is focused on the properties of fresh concrete. Third, the hardened concrete mechanical properties are dealt with, using a model of aggregate particles surrounded by a cement-based matrix.

2.1. Compressive packing model (CPM)

This model is the third generation of packing models developed at LCPC. The aim is to predict the packing density of a polydisperse mix, from the knowledge of three types of parameters:

(i) packing density of monosize classes,
(ii) size distribution of the mix and
(iii) compaction energy.

It is based upon the concepts of virtual packing density and compaction index.

2.1.1. Virtual packing density of an assembly of particles

For a given population of grains, it is well known that the packing density, which is the ratio of the solid volume by the total volume of the container, depends on the placing process. The virtual packing density is, by convention, the maximum value, which is attainable by placing the grains one by one, without altering their shape. Industrial mixtures are always randomly placed, with a finite energy, so that the experimental packing density is lower than the virtual one.

Let us consider a mix of particles of any shape, divided into n classes of monosize particles (with respect to conventional sieving process). In any mix, one may define the dominant class i, which forms itself a packing in the voids of the coarser particles (see Fig. 1). Let β_i be its residual packing density, that is the virtual packing density displayed when the class is isolated and fully packed. The packing density of the overall mixture is computed by noting that the bulk volume of the class i fills the space around the coarser grains; moreover, the volume of finer classes inserted in the voids of class i must be added. Two interaction effects must be accounted for in this calculation: the *wall effect*, exerted by the coarser grains, and the *loosening effect*, exerted by the finer particles. In the model, it is assumed that those interactions are additive, which means that a possible intersection between the perturbed zones is neglected.

2.1.2. Actual packing density: the concept of compaction index

The previous idea, when applied to a n-class mixture of particles leads to the calculation of n equations of the virtual packing density, each one being valid when the corresponding class is dominant. The 'real' virtual packing density is

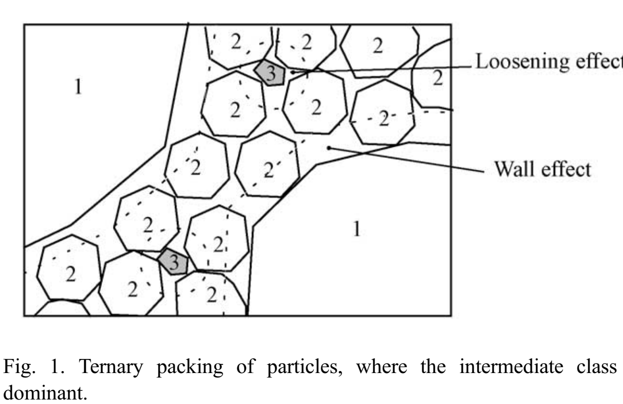

Fig. 1. Ternary packing of particles, where the intermediate class is dominant.

the lowest of these n values. Another parameter, called the compaction index K, is necessary to compute the actual packing density. It expresses to which extent the actual packing is close to the virtual one. Therefore, K appears as a characteristic of the placing process. Mathematically, it is defined as the sum of partial compaction indexes K_i corresponding to each class i. K_i is governed by the actual volume of i grains in the mix Φ_i and by Φ_i^*, the maximal value of Φ_i if the mix were fully packed by an excess of i grains, all the remaining classes having a constant volume. The equation is:

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{\dfrac{\Phi_i}{\Phi_i^*}}{1 - \dfrac{\Phi_i}{\Phi_i^*}} \tag{1}$$

When the solid concentration increases from zero up to the virtual packing density, the packing index grows from zero to infinity. For a given mixture, fixing a K value provides an implicit equation that has only one solution: the actual packing density predicted by the model.

2.1.3. Accuracy of the model

To be usable, the model needs a general calibration, in order to quantify the granular interactions (wall effect and loosening effect), on one hand, and the compaction indexes (K values) corresponding to the various placing processes, on the other hand. This work was carried out with numerous data, either original or extracted from the literature. Now, let us assume that the model is to be used for predicting the packing density of any combination of some elementary classes. Then, the individual packing density of these classes must be measured, from which the β_i values are deduced. At this stage, the model is able to calculate the packing density of mixes, from the size distribution (controlled by the mix proportions) and the K value. Generally speaking, the accuracy is better than one percent in packing density absolute value.

Owing to its good predictive capabilities, the model allows the user to search combinations of optimal packing density. It raises doubts about the concept of ideal grading curve, a popular idea in many mix-design methods: quite obviously, the optimal size distribution over a given grading span depends significantly on the shape of the particles. This could be the reason why many different curves are suggested by various authors. The CPM predicts distributions that depend on the various β_i values.

2.1.4. Application to segregation ability: the filling diagram

The assessment of the stability of a mixture, that is its resistance to segregation, is performed through a new tool entitled 'filling diagram' (see Fig. 2). First, the granular material is divided in a series of clustered classes, each one having a ratio of extreme sizes D_{max}/D_{min} equal to 2.5. Then, the filling ratio Φ_i/Φ_i^* relative to the class i is calculated. Φ_i stands for the volume of i grains in the compacted mixture, while Φ_i^* is the maximum value of Φ_i that could be introduced, all other granular volumes being constants. An ideal size distribution, from the stability viewpoint, would generate a uniform filling diagram.

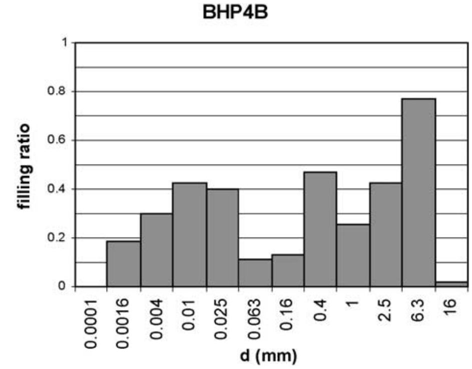

Fig. 2. Filling diagram of a granular mixture. Each peak corresponds to the height of the considered fraction, if it would be fully packed and totally segregated in the bottom of a container.

It turns out that the search for a maximum packing density leads to higher extreme peaks, with regard to the other ones. This is because the finest class, or the coarsest one, has to replace the lacking finer, or coarser grains, respectively. A gap in the filling diagram indicates a discontinuity in size distribution, which is generally considered as a factor for segregability. Then, the filling diagram allows the user to make a diagnosis of a granular mixture and provides guidance in case of excessive segregation.

2.2. Fresh concrete properties

2.2.1. How to describe scientifically the flow and placement of fresh concrete

Between the mixer and the form, fresh concrete may undergo two types of elementary deformations: it may be sheared and/or compacted. For very dry, bulking concretes, compaction is the critical step. On the contrary, for very fluid mixtures like self-compacting concretes, the important phenomenon is the shear deformation (since gravity alone ensures the mixture compaction).

Compactability is directly described by the compaction index, that we will call K' in the case of fresh concrete, to make a distinction with that of the corresponding dry mixture. K' is a major mix-design parameter. Unfortunately, there is today no way to measure it, to the best of the author's knowledge. As for the shear behavior, it is well known that, in the range of soft-to-dry consistency, fresh concrete may be viewed as a Bingham material; in other words, its rheological behavior is described by a straight line in a diagram giving the shear stress vs. strain gradient (see Fig. 3). The intercept of the line is the yield stress and the slope is called plastic viscosity. Within these two parameters, the former is closely related to the slump. The latter makes the difference between a 'worker-friendly' HPC from

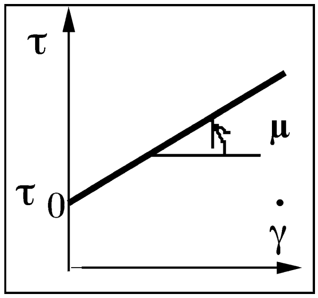

Fig. 3. The Bingham model for fresh concrete.

those having a 'sticky' behavior, being hard to pump and displaying coarse bubbling at the form removal.

2.2.2. Prediction of plastic viscosity, yield stress and slump

The yield stress is a common feature of fresh concrete and dry granular materials (like soils), while plastic viscosity tends to relate fresh concrete to viscous bodies like oils or water. Therefore, one may assume that the yield stress is the result of intergranular friction during concrete shear, while plastic viscosity is the macroscopic signature of the flow of water in the porosity of the granular system. As for the viscosity of Newtonian materials, plastic viscosity is governed by the relative concentration of the mixture (see Fig. 4), defined as the ratio between the proportion of solid materials (in volume) and its packing density. This last parameter can be viewed as the maximum solid proportion corresponding to a nonworkable, water-saturated fresh concrete. From this assumption, it can be concluded that the contribution of the various grain fractions contribute to the plastic viscosity only to the extent to which they contribute to the packing density of the corresponding dry mixture.

The pattern is different if the yield stress is considered. As a matter of fact, a small particle assembly contains more interparticle contacts than a large particle packing. Thus, the friction generated is higher, for a given compaction index. In order to predict the yield stress of fresh concrete, one must add the contributions of the various grain fractions, which depend on their partial compaction index, weighed by a coefficient. This 'friction' coefficient increases when the particle size decreases. The cement friction coefficient may decrease in a 5:1 ratio when a superplasticizer is added: this is the lubricating effect of the admixture. Moreover, superplasticizer exerts also a deflocculating effect, which can be measured through the decrease of water-demand, giving a higher residual packing density in the frame of the packing model. Finally, the yield stress model may be converted into a slump model, having a mean precision of about 4–5 cm. The influence of the various mix-design parameters is predicted correctly, as can be seen in Fig. 5 for a series of superplasticized mixtures made up with the same components.

2.2.3. Fresh concrete stability

To design a concrete having satisfactory fresh properties, it is not sufficient to deal with compactability and rheology. Bleeding and segregation have also to be controlled. Segregation can be predicted through the filling diagram, which must be as uniform as possible. For limiting a gravel/mortar separation, attention must be drawn on the coarse aggregate peak, which should be not too high; moreover, a gap in the sand should be avoided. As for bleeding, it seems to correlate with the height of the peaks in the fine region: the higher the peaks, the less bleeding appears. In presence of superplasticizer, these peaks have to be even higher (more fine particles being necessary to limit the bleeding phenomenon).

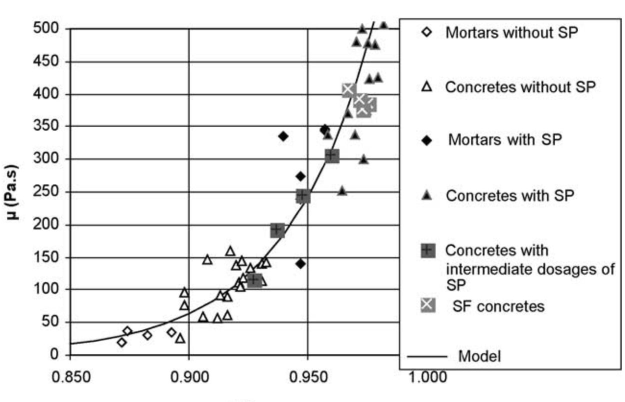

Fig. 4. Relationship between plastic viscosity and relative solid concentration. SP = superplasticizer, SF = silica fume.

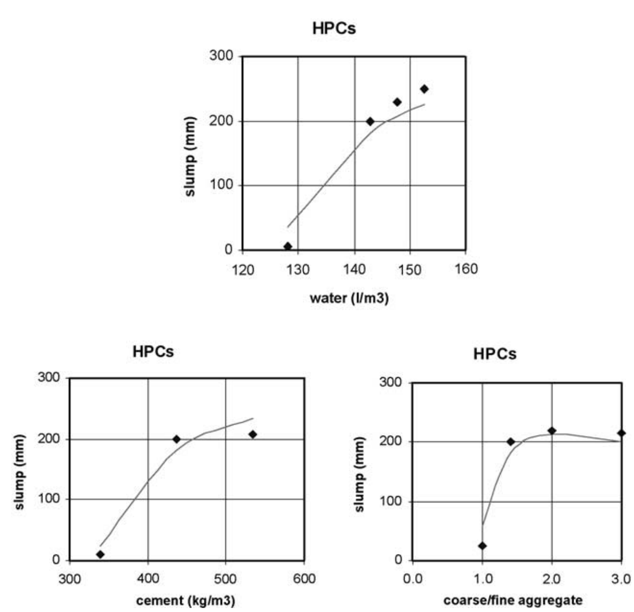

Fig. 5. Validation of the slump model for a series of superplasticized mixtures. No fitting was performed and the model was used on a purely predictive manner.

2.3. Hardened concrete properties

2.3.1. Heat of hydration

Cement hydration and pozzolanic reactions produce heat, which may provoke important temperature rises in massive structures. Such a high temperature may be a factor for cracking during the cooling phase, or may facilitate a delayed ettringite formation. Thus, it is important to be able to control the heat to be produced by a given concrete at the mixture-proportioning stage. The heat capacity, degree of hydration of the cement (or degree of pozzolanic reaction for fly ash or silica fume) and the heat released by a unit mass of reacted binder was evaluated. From these preliminary models, a model of adiabatic temperature rise was developed, giving a mean precision of about 2 °C.

2.3.2. Compressive and tensile strength

The water–cement ratio is the most common parameter used to predict compressive strength. As a matter of fact, this parameter describes the cement concentration in the paste, which is accounted for through a power law (as in the famous Féret's formula). Once the paste is 'injected' in the voids of the granular mixture, its apparent properties are modified by the topology of the aggregate phase. More precisely, it is the mean distance between two adjacent coarse aggregates, called "maximum paste thickness" (MPT) that is critical: the lower the MPT, the higher the strength. Moreover, the bond level between aggregate and matrix, and the intrinsic aggregate strength, also play a role. All these considerations lead to a global model for compressive strength from 1 day to 1 year of age, applying to mixtures containing aggregate fractions, Portland cement, pozzolans and limestone filler. Its mean accuracy is around 2–3 MPa.

Tensile strength is evaluated from compressive strength, as in most construction codes. However, the model incorporates an aggregate coefficient, which increases its accuracy.

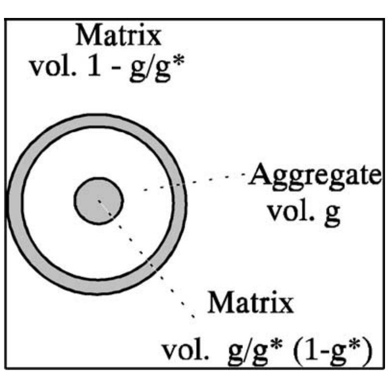

Fig. 6. The triple-sphere model, for the calculation of deformability properties.

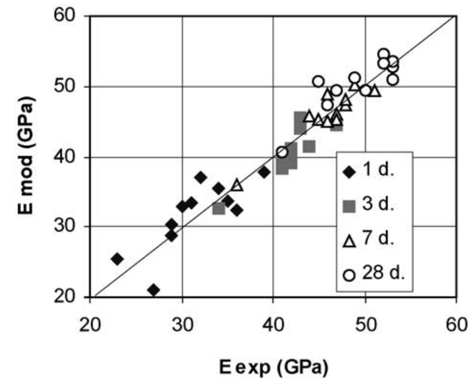

Fig. 7. Example of validation of the model for E-modulus.

2.3.3. Deformability

The deformability of hardened concrete is calculated through the triple-sphere model (see Fig. 6). The intermediate layer stands for the aggregate. The matrix is distributed between an internal nucleus and an external layer. The former corresponds to the paste, which would remain in the 'squeezed' fresh concrete, where the aggregate phase would be fully compacted. The latter is then the 'excess' paste, which gives to the fresh mixture its workability. Applying a hydrostatic pressure to the triple-sphere, one may calculate analytically the instantaneous and delayed deformations, from those of the phases. This approach is applied to the prediction of elastic modulus (see Fig. 7), basic and drying creep. The same geometrical model allows the computation of free deformation, which can be shrinkage (autogenous or drying shrinkage) or swelling.

Finally, it is realized that most important engineering properties, dealing with concrete at fresh state, early and 'mature' age are covered with suitable models. To date, no models are available for durability. This gap will have to be filled in the future. Especially, properties like gas-permeability, chloride ion diffusivity, carbonation rate or scaling resistance will have to be quantitatively related with mixture-proportions. This constitutes an exciting challenge for all the concrete research community.

3. Example

Hereafter, a real example is presented, showing how such a scientific approach may help to solve a new problem, for which no experience is available.

3.1. Performance specifications

A HPC was to be formulated for a specific pavement application [5]. Here, the aim was to cast a thin, unbonded, continuously reinforced concrete slab over a thick, cracked cement-treated base layer. The lack of bond between the two layers was essential to avoid reflective cracking. The top layer

Table 1
Mix design and properties of a special high-performance concrete for pavement

	Specifications	Theoretical mixture	Actual mixture
Coarse aggregate 2/6 (kg/m^3)	$D_{max} \leq 6$ mm 60% of total aggregate volume	935	912
Fine aggregate 0/4 (kg/m^3)		623	608
Cement (kg/m^3)		406	408
Limestone filler (kg/m^3)		101	139
Silica fume (kg/m^3)	10% of cement content	40.6	39
Superplasticizer (kg/m^3)		4.35	5.62
Water (l/m^3)		185	190
Compaction index	≤ 7	6.9	
Slump (mm)	= 150	150	160
Plastic viscosity (Pa s)	≤ 350	350	120–250[a]
Compressive strength at 28 days (MPa)	= 80 MPa	80	78.1
Total shrinkage at 50% RH (10^{-6})	≥ 750	750	

[a] After 60 min.

thickness (60 mm) was determined by the constraint of steel protection against corrosion. However, a dense concrete containing silica fume was necessary to provide such a protection. The amount of coarse aggregate was imposed by the skid resistance requirement. For the sake of wear resistance, a compressive strength of 80 MPa was specified. In order to facilitate the casting process, a slump of 150 mm was required, with a suitable placeability and a limited plastic viscosity. Finally, the risk of buckling by hot weather had to be managed (since the top layer was just lying on its foundation). The remedy consisted in choosing a high-shrinkage HPC. In this case, the restrain provided by the infinite length of the pavement is assumed to keep a sufficient level of tension, even when concrete warms up to 50 °C. The final set of specifications appears in Table 1. Let us point out the unusual character of this set, as compared to conventional HPC, where the maximum size of aggregate is much higher, and shrinkage is generally minimized.

3.2. Mixture-proportioning

After a careful characterization of local constituents, an automatic optimization was performed with a software incorporating all models previously presented [6]. The optimization criterion was the unit cost of the recipe. Simulations showed that limestone filler was helpful to match the shrinkage requirement at a limited cost. The theoretical mix-composition appears in Table 1. After the production of a trial batch, minor adjustments were carried out to obtain the required rheological properties, producing the actual recipe given in the last column of the same table. This mix-composition proved to be satisfactory.

4. Conclusion

• A new, scientific approach is proposed to design cement-based materials based on performance specifications.

• A comprehensive set of models has been developed, covering all the concrete life-cycle but the long-term degradations.

• The models may be incorporated into software. With the help of a solver module, automatic optimization is possible, involving both technical and economical considerations. This process leads to very realistic mixtures, in accordance with state-of-the-art materials used in the industry. A wide variety of concretes can be simulated, from everyday, low-strength concrete for building to HPC, including self-compacting mixtures or sprayed concrete (among other categories). Such a software package is now available in France [6], based upon the models given in Ref. [4].

• Material data must be stored in a data base. Therefore, it becomes easy for the engineer to envisage a wide variety of possible components for producing ‘à la carte’ concretes. This new approach does not suppress the need of laboratory trial batches. But the material and labor expenses are greatly reduced, and a better use of past experience can be made.

• To complement this type of approach, more research is needed in the field of durability. In the future, one may expect to see service life duration being specified on a routine basis. For such a prediction, the use of cellular automaton techniques like the NIST model [7] certainly has a great potential.

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