Concrete mix design method according to referential structure and the aggregates specific surface area

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ABSTRACT

This research presents new procedures to calculate the aggregates weight and the water requirement to realize a controlled concrete mixing design, where the aggregates proportion is defined by numerical method according to referential curve draw as referring to the proposed fine aggregate ratio and the required water will be calculated as referring to the aggregates surface area. The results showed the facility and the reliability of the proposed design procedures.

KEYWORDS: ready mixed concrete, modeling, optimization, specific surface area.

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1. NTRODUCTION

During the last decades, the ready mixed concrete research has had to solve the problem of durability and try to resolve the problem of carbonation, leaching, chlorides and sulfatic attacks as well as other malicious phenomena[1].

In addition to the scientific achievements, all these works agree on the importance of understanding the properties of concrete and to ensure the batch a better density[2], thus revive the question of the structure grading in concrete its great importance.

So considerable research has been devoted to provide aggregates proportioning methods and various options to calculate the required mixing water, wherein its quantity is in balance between two non harmonious criteria the strength, on one hand, and the workability, on the other.

2. PROBLEMOFCOMPOSITINAND QUALITY ASSURANCE

After the composition of the batch and the control of its quality by a laboratory trial test, monitoring and quality assurance remain the primary missions during the production operation. Therefore, even if the advantage of the production in the central-mixed concrete relative to the yard is the possibility to control the variability of the various parameters, the disadvantage remains for the engineer in that he must manage with substantial variability of aggregate specification for reasons of cost effectiveness or contractual commitments.

The question which appears during the modeling is the agreement of the physical and mechanical properties of the various granular components, with the hypothetical characteristics of aggregates taken into consideration during the composition. Admittedly, it would be absurd to produce a so-called perfect copy generated by own calculations, so that we have to introduce into the production system the concept of an uncertainty margin which allows to evaluate the quality of the concrete aggregates by a range of values often expressed by the granular curve zones.

In confronting this situation where the variability of granular materials can be huge, the engineer must honor the commitments of production by controlling variables, and the treatment of all its consequences. This mission is the most important aspect among the daily duties of an engineer.

Although the engineer can take control measures to assure quality in a short or a medium term, he may nevertheless be unequipped to make instantaneous decisions to fix accident related problems.

3. RESEARCH SIGNIFICANCE

In this spirit author conducted research to solve the problems of composition and quality control. This work presents a formulation model which ensures the following points:

- Obtaining granular compositions of the blended aggregates which fulfill two conflicting requirements: strength and workability.
- Choosing between several optimization solutions by a quality criterion attributed to this model.

This model presents the advantage of being integrated into the tools of computing and into the automated manufacturing systems as well as being compatible with the system which controls and assures a product of quality.

4. REVISIONANDINVESTIGATION OF GRADING CRITERIA

The formulation of the model was initiated by a revision of the various concepts and methods of aggregate composition and studied the substantive principles of various basic concepts to better understand the requirements ofmodeling.The Specific MassThesemi-empirical odels of proportioning concrete mix such as Abrams[3], Dreux et al[4], and others, are based on the determining of the weight of constituents.

In general, the aggregates used in the composition of concrete do not have the same mechanical properties. The techniques of crushing, based on the explosion of rock masses, then undergoing successive crushing to obtain the required aggregate size, explain this difference.

Often, the coarse and medium aggregates belong to the same deposit whereas the local crushed sand is produced from the tender rock masses and the rest of crushed hard rock within a little quantity of silt, clay, and flying particles classified as none prohibited.

Another factor is the different mineralogical nature of the natural fine sand which is taken from the desert site, or the alluvium sedimentary non-consolidated formation.

These resource requirements make the physical properties such as the bulk specific gravity and the bulk density of various aggregates not identical **(shown in Table 1).**

Furthermore, the major difference between the bulk specific gravity and bulk density of cement means that the aggregate composition obtained by the weight method always shows an underestimation of the sand volume and an overestimation of the cement volume.

A misleading estimation of the various concrete components density may also be unintentionally attributed to concrete aggregate compositio This factor exacerbates the inappropriateness of the composition during the production.

(See Fig 1.)

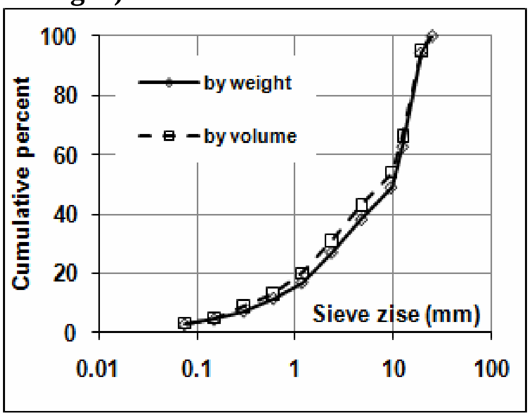

Fig. 1 – Misleading of aggregates volume.

Relative to the coarse aggregates 12.5 - 25 mm, this poor estimate may be in the order of 4% and 6% less in volume respectively for the crushed sand and the fine natural sand, and reaching 13% more in volume for the cement, as shown in **Table 1**.

This question becomes fundamental to the concrete formed by constituents of different nature, such as blast-furnace slag for heavy concrete, or natural and composite light material such as aggregates of pozzolan , expanded clay, cork, stereo-pore …etc, for lightweight concrete.

4.1.Finesse Modulus and Specific Surface Area

In 1918, Abrams proposed the Finesse Modulus to evaluate the quality of aggregates involved in the proportioning of concrete and to estimate the quantity of water requirement.

This modulus is presented schematically in the semi logarithmic curve by the surface formed above the grading curve of the aggregates. Its value is presented as being equal to the sum of the accumulate percent of retained on standard sieves 0.15 - 4.75 mm (N°100 to N°4) for sand, and up to D_{max}= 75.0 mm for the large size-graded aggregates[5].

ACI[6, 7] and ASTM[8, 9] recommend the values 2.6 to 2.8, and 5 to 5.2 for well-graded aggregate that the nominal maximum size D_{max} equals to 25 mm.

The problem which requires some reflection is how precise this modulus may be to assess the quality of aggregates.

Figure 2 shows how designer can have the same value of the finesse modulus for a continuous curve A and a binary curve B; this coincidence should make us question the merits of this criterion.

Another reason for questioning is the strong influence of coarse and medium aggregates on the sensitivity of this modulus.

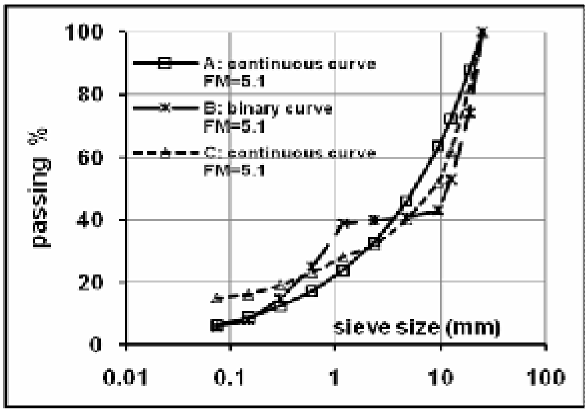

Fig. 2 - Different forms of aggregate curves with an identical finesse modulus

The same Figure shows that an increase in the percentage of fine particles (curve C) may give the same value of finesse modulus by a simple increase in the sizes of the coarse and medium aggregates, which could in certain cases give a misleading assessment of the quality of aggregates and itsreal finesse modulus.

Instead of the finesse modulus, Day[10] has preferred to speak of the specific surface area of particles and modified the value given earlier by Murdoc[11] to take into account the real relation of the various granular components with the concrete mixing water.

Murdoc method was based on the principle of calculating the rates of different aggregates produces a definite value of the specific surface area of composition aggregates.

4.2.The Water Requirement

Usually, the water requirement is defined by the reported water - cement ratio which value varies according to the nominal maximum size of aggregates, the granular characteristics, the consistency of the cement paste, the workability of concrete and other sub factors[12, 13, 14]

Its quantity is divided into two parts: the first part necessary to hydrate the cement, where it is estimated approximately to 20-24% of the cement weight and considered such as sufficient to transform this linking material to a strengthen stone-like with a rate of acceptable workability.

The second part added to make the consistency of the mixture more fluid; this part is the most questionable because of its relationship with the properties of aggregates; in general and relatively to the range of mixing concrete aggregates, the quantity of the batch water may overtake the 50% of cement weight.

Looking at the the relationship between the aggregates and water, a film of water surrounding a particle of cement cover fine particles of its environment and the whole of the mortar is tangent, at the same time, to the coarse particles of aggregates. Thus, the water used for hydrating cement should define the consistency of the mortar and also the whole of the concrete mixture in a simultaneous manner[15].

Furthermore, a part of the water estimated necessary to form the mortar will contribute to the movement of the coarse aggregates of its entourage; this must reduce and minimize theroleof coarse aggregates in the estimation of the quantity of water necessary to give the mixture the expected handling and workability.

This redundancy of the relationship between the aggregates and the water leads us to accept that the more the size of the aggregates increases, the more its influence on the estimated required water decreases. Hence, to look with greater precision at the concept of the relationship between the specific surface area and the water of the aggregates mix, which will be discussed in the following section.

Table 1 - The maximal proportion of aggregates compilation for 1 m^3

Description	Coarse 12.5-25	medium 6-12.5	fine 0-6	natural 0-1	cement		water
Bulk specific gravity kg/m^3	2790	2790	2670	2650	3150		1000
The specific gravity report relatively to the coarse aggregates	1.0	1.0	0.96	0.95	1.13		-
Oven dry rodded density (OD) kg/m^3	1350	1350	1600	1450	1300		-
Initial % volume before filling	100	51.6	26.5	10.6	4.8		2.8
% Volume of material	48.3	25.0	16.0	5.8	2.0		2.8
Weight of material Kg/ m^3	1350	696	424	154	62		28

4.3.Trial test of Maximal Mass Density Compilation

Takingint account the properties of materials constituting the concrete **(**Table 1**)**, the solid constituents of concrete including cement were filled in unit volume, according to a range of order, where the water was filled up the porosity. By this process the maximum mass density of the concrete batch was reached, in which the aggregates are 95% of the unit volume: 73% for the retained particle and 22% for the passed by the sieve 4.75 mm (No 4).

The cement and water make up only 5% of the volume. The concrete batch unit mass reaches 2716 kg/m^3 and the water cement ratio *W/C* is equal to 0.45. The compactness of these aggregates is certainly very great and the mixture is difficult to work

(Note that the air-entrained concrete[6] was neglected and this formulation concept remains theoretical).

In amending this grading structure by a decrease of the rate of coarse and medium aggregates on the order of 30%, allowing to give the batch better workability and to detect the strong influence of coarse and medium aggregates on the batch consistency.

Table 2 shows the percentage of the various components of two solutions and the ratio G/S percent of coarse/sand as well as the evaluation of the workability.

This process approaches the aggregates grading from a power form that may be a solution for a well graded aggregates for a better consistence concrete batch(**Fig. 3**).

Table 2 – Percent volume of aggregates

Description	Crushed aggregates			Dune	G/S
	12.5-25 (mm)	6-12,5 (mm)	0-6 (mm)	0-1 (mm)	
maximal	51.4%	26.5%	16.0%	5,8%	
modified	31.1%	22.6%	34%	12.3%	
maximal	77.9%	21.8 % (compact)			3.5
modified	53.7%	46.3% (handing)			1.16

Mechanically, the reduction of coarse and medium aggregates gives the different solid particles more freedom to move around and to rotate, and this explains the increase in workability.

Therefore, in order to control the workability of the batch, we must define the percentage limits of the concrete aggregates for each granular category.

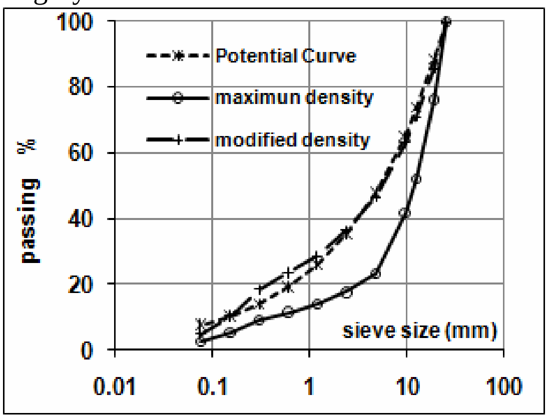

Fig. 3 - Comparison between the maximum density curve and the modified density curve.

5. ANALYTICAL INVESTIGATION

The revision of these various concepts and aggregate composition method helps to better understanding the requirements of modeling; thus, on the basis of the volumetric granular algorithm presented above, a grading model will be proposed here taking into account the following points:

- The possibility to form the grading of batch on the basis of granular volume.
- The validity to simulate the volumetric grading curve with an exponential "curve model".
- Mainstreaming of the specific surface area in this method and considering it as the best placed parameter to describe mechanical properties of particles of the concrete batch.
- Proceeding by optimization to define the rate of each range of aggregates.

5.1. Proposed Grading Model

In this model the passing percentage of aggregates was expressed in volume unit; the grading curve is given by the potential expression:

$$P\% = K\, D_{max}^{G} \qquad \textbf{Eq. 1}$$

Wherein *K* and *G* are correlated by a logarithmic relationship for each level of required nominal maximum sizes of aggregates (**Fig. 4**); for D_{max}= 25 mm, *K* is equal to:

$$K = 0.31\, Ln(G)+1.43 \qquad \textbf{Eq. 2}$$

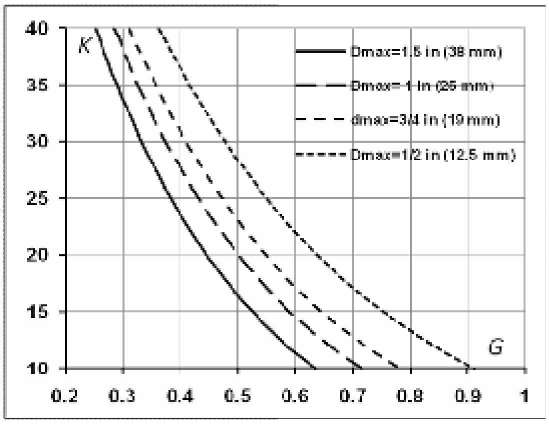

Fig 4. Relation between K & G

5.2. Required Water and Evaluation Criterion

Based on the analysis of the relation between aggregates, that was simplified above, the aggregates specific surface area was considered to be the best criterion to evaluate the simulated solution which will define consequently the quantity of water necessary for the batch of the concrete.

A thorough statistical study, which was conducted on data collected on the central-mixed concrete where the reported slump was around 150 - 175 mm, as recommended by ACI for pumped concrete[16] (See Fig 5 & 6).

This study has enabled to propose a linear regression relationship between the basic required water *Wcs* (by liters or kilograms) and the aggregates specific surface area values *Sa* (m^2/Kg) of series of aggregates 75 µm to 4.75 mm (No 200 to No 4) given by Day[10].

Its relationship with *Sa* takes the form:

$$W_{CS} = (S\, P.Sa\, .\, q) - 20 \qquad \textbf{Eq. 3}$$

Mechanically, W_{CS} encompasses the basic hydraulic aggregates nature able to assure the good workability; its value depends on *q* considered such as a macro structural parameter which describes the hydraulic characteristic of aggregate in micro level[17]. wherein *q* value estimated between 50 and 60 mL/m^2

When optimization process, the grandeur of W_{CS} (without measurement unit) is taken such hydraulic evaluation criterion; it may be used to evaluate the hydraulic aggregates properties, the quality of the concrete grading and the proportioning report between its aggregates.

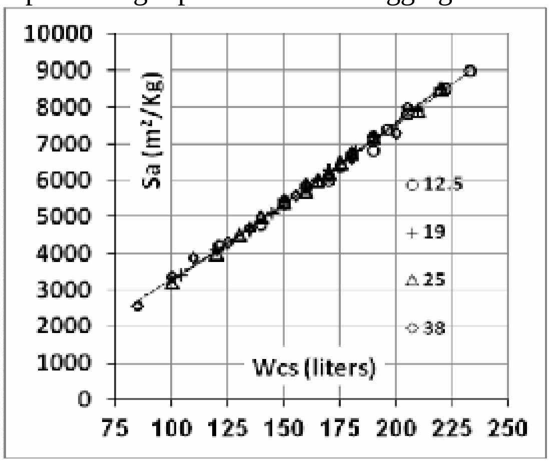

Fig 5. Correlation between the specific surface area and the basic requirement water

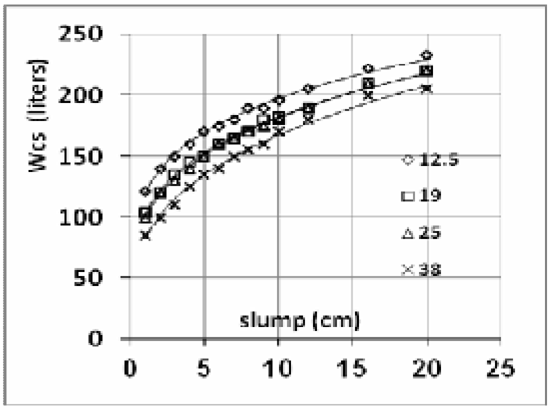

Fig 6. Relation between the Abrams slump and basic requirement water

A quantity of estimated absorption water W_{ab} for the total coarse and medium aggregates weight P_c retained on the sieve 4.75 mm (No 4), must be added; its value is proposed by the equation:

$$W_{ab} = SP_c \,.\, w\% \qquad \textbf{Eq. 4}$$

This value must be adjusted by quantity of water $W_{C°}$ to cover the evaporation, and quantity *Ws* necessary to cover the quantity of cement greater than 250 Kg and to improve the subsidence[17].
So, the general formula for the free required water could be given by the expression:

$$W_m = Wcs + W_{ab} + W_{C°} \pm Ws \qquad \textbf{Eq. 5}$$

5.3.Proportioning by Simulation

A system process of optimization "RMCPD", that was already developed, will be used for choosing the optimal proportioning of the concrete aggregates. This system comprises:

- A digital program of simulation wherein integrated the equations design is presented above.
- A computerized database, including the values of the specific surface area, will serve for the simulation and the qualification of results.
- The granular graduation of the four local constitutive aggregates and their physical properties.
- The specification of the required concrete.

The program takes into account aggregates available in stock and seeks to propose, according to the number of solutions demanded by the user, solutions in the form of the granular graduation curves with their four proportions granular substances.
The advantage of this system model is that we do not have to consider the quality of our results in relation to a standardized zone data curve but to a well defined referential curve, which makes the vagueness of any measure negligible compared to the quality of procedure.

6. PREDICTIONS AND EXPERIMENTAL RESULTS

Using the local aggregates in Figure 2 and Table 1, this process starts by the preparation of data and finishes by the evaluation of optimized solutions and the choice of the optimal proportioning of the concrete batch aggregates.

6.1. Water Requirement

To verify the validity of required water model (***eq. 5***), the different partial values of water quantity described above were calculated for the theoretical grading curves of D_{max} is equals successively to 37.5 - 25 - 19 - 12.5 mm, and for the following conditions:

- Ordinary Portland Cement OPC= 300 Kg/m^3,
- Ambient temperature = 22 °C,
- The slump S= 175 mm,
- The absorption rate for medium and coarse aggregates $w\%$ = 0.5%,
- The hydraulic surface area rate q = 52 mL/m^2,
- The percentage of fine particles 75 µm (No 200) equals to 8% .

Thus, the value of W_m were respectively 191.6, 203.1, 210.6, 227.6 Kg/m3; while the American Concrete Institute[6] proposes the values of 190-202-216- 228 Kg/m3 for the same condition (**Table 3**).

Table 3 - Required water quantity for the four maximum nominal sizes grading

Description Kg/m^3	Maximum nominal size grading mm			
	37.5	**25**	**19)**	**12.5**
W_{CS}	**169.5**	**179.3**	**185.4**	**199.6**
W_{ab}	**7.20**	**8.80**	**10.20**	**13.0**
$W_{C°}$	**–**	**–**	**–**	**–**
W_S	**15.0**	**15.0**	**15.0**	**15.0**
W_m	**191.6**	**203.1**	**210.5**	**227.7**

– Regarding the normal ambient temperature, it is not taken into consideration.

This result shows the validity of the proposed relationships for a first estimate of the water quantity required to form the batch and for a given slump on the order of 175 mm.

6.2. Optimization Grading Curve of Concrete Aggregate

Generally, if the designer works with standard aggregates, the optimization will give a single solution. Admittedly, it would be absurd to have so perfect materials; thus, the optimization objective is to have a better concrete grading aggregates.

Table 4 – Optimization solutions for a "curve model" that Dmax= 19 mm

Description	W_m Kg	Wcs
Curve model	**210.5**	**185**
Optimization (opt 1)	**210.5**	**190**
Optimization (opt 2)	**204.6**	**185**
Optimization (opt 3)	**192**	**172**

To verify the validity of this concept, an optimization process was realized to get better grading solution that D_{max}= 19 mm and 8% of fine aggregates 75 µm (sieve No 200).

The optimization was carried out with the suitable "curve model" that the referential value were *Wm*= 210.5 Kg/m^3, *Wcs*= 185 , and therefore gave three solutions opt 1, opt 2, opt 3, (**Table 4, Fig. 7**).

6.3. Optimization and Quality Control

The three simulations show an interesting divergence with the "curve model" in the fine aggregate size zone that could be explained by the use of defect harsh crusher sand stocked in site.

Thus, the Designer must choose the suitable optimization solution, referring to three criteria : the value of the water batch *Wm*, the value of the consistency Index *Wcs*, and the grading curve form.

In all cases the decision should be validated by a trial test where the result could be a bases for the quality control and all future decision.

In Figure 7 we have three curves from three sets of aggregates with a three value of Wcs; the result of the simulation shows us a certain defect in the grading of curve B (points 1, 2, 3, 4) that we explain by the non compliant grading aggregates found in stock.

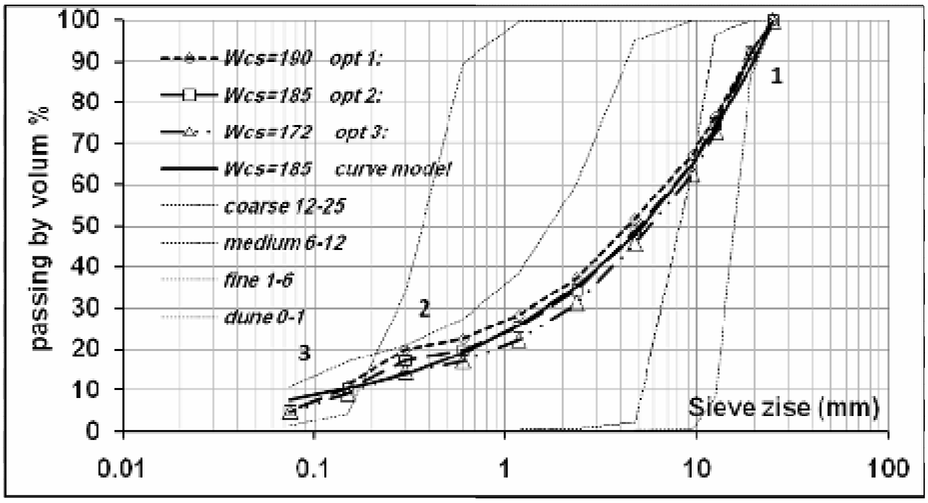

Fig 7. Concrete aggregates composition and quality Assurance

Therefore, we should inform both the aggregates supplier and the laboratory and the stationary mixer to take the technical measures necessary during the production and to correct some missteps which can occur by either overusing or under using mixing water.

7. COMPLEMENTARY OPERATIONS

It is obvious that the density method is difficult to use for proportioning the 4 constituents of aggregates, particularly when the manufacturing technology of concrete uses electronically sensitive weighing hoppers. It would be better to move from the state of modeling to the state of production by transforming volume to weight.
Undoubtedly, our method requires verifying from time to time the value of this parameter. We have shown that the most sensitive materials are the crushed and the natural sand, and this verification is easy in that we need only a single standardized receptacle whose volume is known to take its real wet weight. Then we can extract, by a simple calculation, the value of the apparent density of its real state in the storage park and on the conveyor belt of the weighing hopper.
As we have reported, a quick calculation must be done to give the monitor instructions for such a change

8. Model Validity

To validate the reliability of our model and the procedures described below, we realized tests to show the advantages of the method. We use the 4 substantial aggregates present in the central-mixed concrete, described below, whose mineralogy of the three aggregates is the calcite and the natural sand is silica. We have prepared 3 batches whose the cement quantity is respectively 350, 400 and 450 Kg (Grade 32.5), with and without the use of reducer water (type F) and retarder (type G) (ASTM C 494 / C494 M).
The quantity of the estimated initial mixing water has been calculated by the relation [5], corresponding to a slump on the order of 175 mm. For quality control, 8 cubic specimens (size cm) have been taken for each batch. These specimens are kept in standard conditions, and then tested in axial compression for different ages (Table 5).

Table 5. Results of resistance for axial comprive strength (kg / cm^2)

N°	Cement kg / m^3	Age (days)					W / C	Slump Init / fin (mm)	Admixtures liter per 100 kg cement
		3	7	28	40	56			
		without chemical admixtures							Redc. / Retd.
1	350	174	226	342	395	390	0.56	105	-
2	400	192	276	373	409	420	0.50	110	-
3	450	224	290	414	443	462	0.46	100	-
		with chemical admixtures							
4	350	215	361	381	407	401	0.52	35 / 170	0.6 / 0.16
5	400	251	424	437	469	438	0.45	30 / 170	0.6 / 0.16
6	450	297	437	483	500	519	0.40	45 / 180	0.6 / 0.16

9. DISCUSSION OF RESULTS

The test result of the optimization process and the water estimation method approve the following point:

- The proposed optimization method has helped to well structure the aggregates composition batch.
- The amount of the required water can be well calculated relatively to the real aggregates grading.
- The proposed consistency index allows to better control the aggregates grading and the proportioning between different aggregates sizes.
- With this mastery of granular structure, the reduction of water requirement on the order of 10% (specimens' N° 4, 5 and 6) has allowed us to increase the strength of concrete at a rate of 12 to 16%.
- The quantity of chemical admixtures has also been reduced to one half of the rate recommended by the manufacture specifications, 0.32 and 1.2 liter per 100 Kg cement for retarder and for water reducer respectively.

Therefore, it may be possible to accept a most likely appropriate curve who's *Wcs* no longer close but where the equilibrium between its granular constituents is more coherent. In this case it must be careful to revise the quantity of required water for the concrete mixture.

The real quality of the computerized composition is not only the excellent proportioning but also the possibility to judge the quality of materials on stock in the central-mixed concrete.

10. CONCLUSION

The formulation and the proportioning of concrete remain dependent on the variability of the properties of its components and contingencies may intervene during the manufacturing.

The method of optimization and proportioning that was proposed with the integrated optimization tools have helped to produce a mixed concrete batch of very good characteristics, subsequently confirmed by applications.

The gain is already exploitable but requires, in our opinion, greater refinement to better address all the problems of manufacture and to develop procedures to be integrated into the system of quality control.

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APPENDIX

The following symbols are used in the paper:

P% = the percentage by volume of aggregates passing by a sieve d.

K : parameter depending on the percentage of the fine particles ≤ 75 μm.

G : parameter depending on the requested nominal maximum sizes of aggregates.

d : the sieve size.

D_{max} = maximum nominal aggregates size.

Sa = the proposed specific surface area proposed by Day[10].

P = the weight of fine aggregate in 1 m^3 of the batch, related to d.

Pc = the weight of coarse and medium aggregates in 1 m^3 of the batch, related to d.

q = hydraulic specific surface area rate it is here on the order of 0.05 – 0.055 Kg/m^2.

w% = water absorption rate for the medium and coarse aggregates.

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