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FORMULATION OF THE DYNAMIC METHOD FOR THE DESIGN OF CONCRETE AND MORTAR MIXES

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Note: The following is the notation used in this paper: (.) for decimals and ( ) for thousands.

Summary

The Dynamic Method for the design of concrete and mortar mixes (MD) is tool used to take decisions in research works, construction of engineering works and continuous improvement programs.

One of its main applications is that it allows to design and budget concrete and mortar mixes by weight and volume, produced with Portland cement, additions, admixtures, etc.

The MD is ideal for producing wet concrete for slabs, columns, beams, etc., and dry vibro-compacted concrete paving and precast units (two-layer tiles, pavers, blocks, etc.), evaluated by the standards that rule the testing methods for compression, flexural, traction and shear tests.

The method is a mathematical and statistical extension of the Marshall Method used to design asphalt concrete mixes. Its base is the "universal principle of the optimal moisture content", which stipulates, "The workability and the final texture of the concrete depend on the same nature of the mixture".

Its name is “dynamic” because after lab testing a concrete specimen, the professional can simultaneously correct the composition of the mix, be it designed by weight or by volume, and adjust the budget.

One of the major benefits of the MD, consists in that the software enables to systematize the processes and to accredit the plant as a whole (ISO 9000, 9001, 9004 and others). It additionally reduces the steps in the production of mixes and the "no" "Conformities", and optimizes the use of materials on site and lowers the costs in transport of samples, quality controls and laboratory tests. All this when the MD is used together with a concrete mixing plant,

Away from the established classic principle "the strength of a concrete or mortar is directly proportional to the water/cement relationship and to the greatest density of aggregates", the MD gives rise to a new dosage theory that extends mixtures applications and facilitates writing and discernment about it, mathematically defining several indexes as: effectiveness factor, workability, cement content, optimal moisture content and texture.

Up to April 2009, the MD has been evaluated for more than 20 years by many contractors in Medellín, COLOMBIA. The software is available in Spanish, and it is expected that the version in English will be available in October.

1. HISTORY OF THE DYNAMIC METHOD (MD)

The Marshall Method has been used worldwide since 1950 in the whole world to design and control hot and cold asphalt concrete mixtures. The author of this paper proposed the extension of this method called "Dosage by percentages (DP) in 1985. He made a research using soil and cement in the Soil and Pavement Laboratories of the University of Medellín, COLOMBIA. The good results allowed applying the extension of the research "Chemically stabilized soil stabilized for popular housing" with the Cimba-RAM block, undertaken in the National University of Colombia (Peval-Cehap) and subsequently in research "Manufacturing of floor tiles with polyester" (polymeric concrete, Andercol). It was also be used in the production of floor tiles and concrete pavers (Roca Industries and Indtustrial de Pisos). It is currently used in Medellín for the control and dosage of concrete and hydraulic mortars in Policoncreto Engineering Laboratory and in teaching, in Cenaltec.

"Concrete Software" is a Web application based on the Dosage by Percentages (DP) and that after the study, the interpretation and careful practice of the Colombian Standard on Earthquake Resistant Design and Construction (NSR-98) (the Colombian structural code), resulted in the MD.

What makes MD peculiar is that it can be used to design al type of mixtures used in construction, either in dry state (vibro-compacted), wet (simple and reinforced), viscous fluid (pumpable) or liquid (self leveling and non self leveling). The primary condition is that the mixtures be controlled in a lab using standardized testing procedures for compression, flexion, traction, friction or shear.

2. CLASSIFICATION OF THE CONCRETE

The main feature of the concrete is considered the workability of the mixture due to the other properties can be easily managed. Therefore, for practical and normative, effects the specific are divided in five groups according to the "settlement" (slump) that requires the structure (see Table 1).

2.1 Types of mixtures according to the settlement

Table 1. Classification of mixtures (type) according to its settlement.

MIXED TYPE	SETTLEMENT (SLUMP) MAXIMUM
Dry	0
Wet	0 mm to 100 mm
Fluid viscous	100 mm to 150 mm
Liquid not self leveling	150 mm to 200 mm
Liquid self leveling	Large: Measure the final diameter

2.2 Analogy between the concrete and men

To understand the mechanical behavior of mixtures in full, it is convenient to associate each of the materials and processes with the physical organs of a human being (see Table 2).

This analogy eases the understanding of what happens internally to a mixture during their production and life, even under the action of an earthquake.

Table 2. Analogy between concrete and men.

Concrete (material)	Human beings (physical composition)
Cement and additions	Joints and muscles
Sand plus coarse aggregate	Skeleton
Water and additives	Blood and nutrients
Physical and design illnesses	Physical and psychological illnesses
Mechanical properties	Quality of life
Concrete strength	First eye
Cement consumption per m^3	Second eye
Traceability	Name of the person stool
Architecture	Language and senses
Functionality	Profitability
Waste during casting	Fecal material and secretions

3. MATHEMATICAL FOUNDATIONS AND STATISTICIANS

3.1 Third Dimension and Concrete Effectiveness Factor

It is known in classical technical literature that strength of a concrete specimen is directly proportional to the Water / Cement Relationship (A/C) of the mixture (see Figure 1). It is also known that the larger amount of cement in the mix, the greater its strength (see Figure 2).

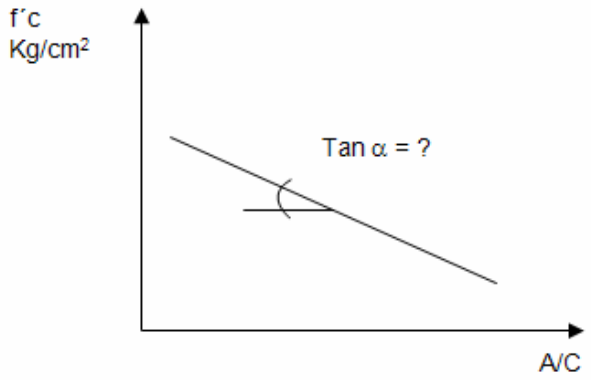

Figure 1. Mix compressive strength vs. Water/cement ratio.

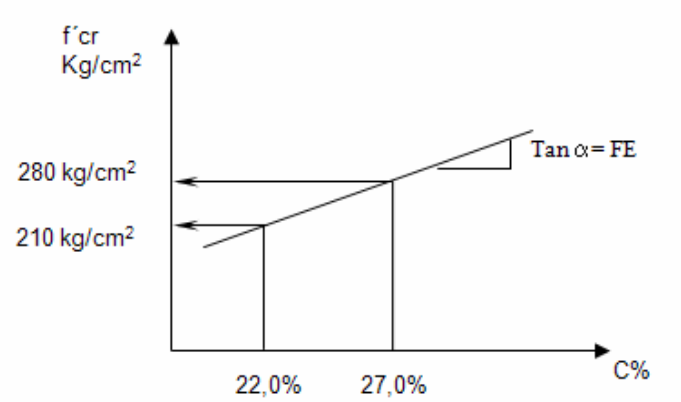

Figure 2. Mix compressive strength vs. Cement %.

It is very difficult to determine for an already placed mix, which is its real A/C relationship. The procedures that use the classic methods are inadequate, because water is a parameter of conflict between the workers and producers. Therefore, to determine the tangent of the straight line of the concrete placed in a work (see Figure 1), it is impossible using the current classical methods.

But to determine the percentage of cement in the mix regarding its dry aggregate is very easy if you know the dosage of the concrete. Therefore it becomes imperative to define the Third Dimension the Concrete (C%), as the percentage of cement needed by the mix (regarding the dry aggregate) to achieve the Average Required Strength of the Mix (f´cr). In this way, it is possible to know the searched theoretical cement consumption (CMt), using the following equations (see also Figures 2 to 4, Equations 1, 2 and 4 and paragraph 3.2):

Equation 1.

$$C\% = \frac{Wc}{Wag} \times 100$$

Where:

C% = Cement percentage required in the mix for obtaining the required strength - Third dimension of the concrete, (%).
Wc = Weight of the added cement to a batch, (kg).
Wag = Weight of the added dry aggregate to a batch (sand + gravel), (kg).

Knowing the C% obtained from Figure 2, or from the experience of previous works and after determining the A/C relationship, which should be corrected using the procedure given in www.cenaltec.com pages or www.cenaltec.policoncreto.com ([1]), you can find theoretical cement consumption so the strength of concrete be the required one. This is done through the following equation:

Equation 2.

$$CMt = \frac{Dh}{1 + A/C + \frac{100}{C\%}} \quad (kg/m^3)$$

Where:

CMt = Theoretical cement consumption obtained by mix design, (kg/m^3).
Dh = Wet density of concrete at the time of production, (kg/m^3).

Equation 2 is a mathematical balance one, which determines the theoretical amount of cement per cubic meter of wet mix needed by concrete or mortar to reach the required average strength (see Equation 4).

For the mathematical balance of the mix, other equations have been found when puzzolans and admixtures are used, but they are not considered in this paper.

The Effectiveness Factor (FE = Tan α) shown in Figures 2 and 3, can be easily obtained in a laboratory, rebuilding the approximate straight line (see NSR-98; paragraph C.5.3.3.2 (e)).

When combined the three previous dimensions, or Figures 1 and 2, on can obtain Figure 3:

To find the Equilibrium Factor ([2]), it is fundamental mathematically determine the CMt and to determine the Real Consumption of Cement Placed in the Structure (CMr), or placed in a known volume. The following equation is then recommended:

Equation 3.

$$CMr = \frac{No. \times Wc}{Vo}$$

Where:

CMr = Real cement consumption in a known volume of concrete, (kg/m^3).
No. = Batches used in a known casting volume, ([1]).
Wc = Weight of cement used in a batch, (kg).
Vo = Actual volume of concrete measured in the work, (m^3).

Similarly, you can define mathematically the Workability (W) and the Texture (T) of the mixes, somewhat extensive equations to deliver in this paper. You can see in Figure 3, the point where you located W and T ([3]).

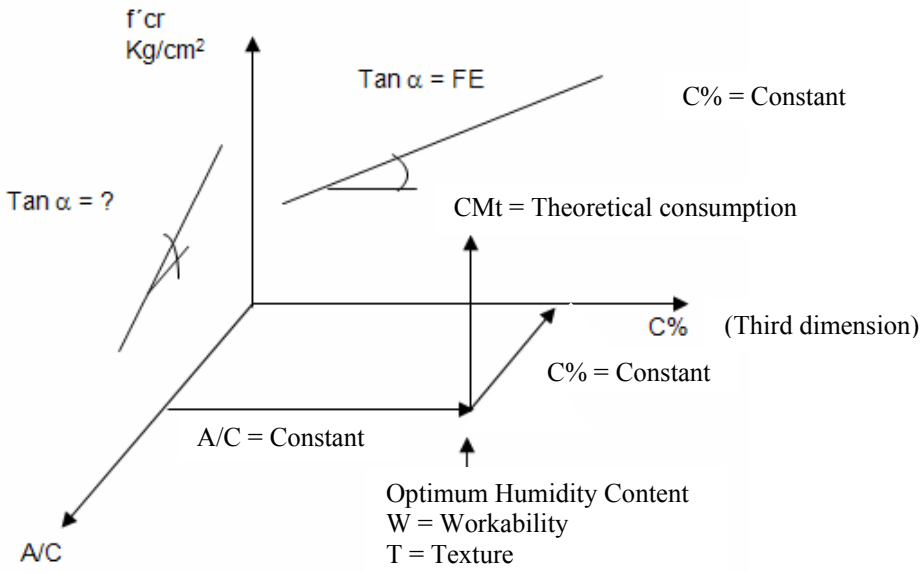

Figure 3. Third dimension of concrete.

3.2 Average Required Strength of the mixture

The Coefficients of *Mayoración* considered in the design of a structure, are different to the Safety Factors required by a mixture due to deficiencies in its production. This condition suggests that the Structural Design or Nominal Strength (f´c), must be less than the strength that reaches the mixture

in its cured state. For this reason, it is necessary to define f´cr or design of the mixture, which shall exceed the f´c (see Figure 4).

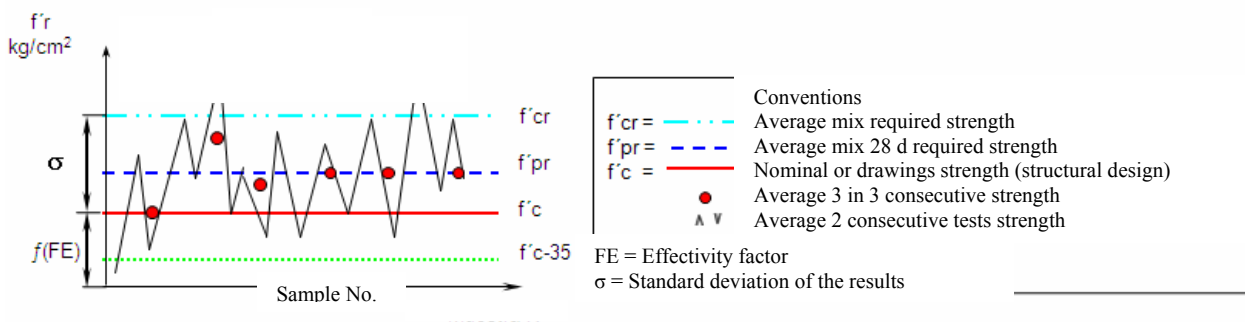

Figure 4. Average required strength.

Can mathematically prove that the resistance of plans or structural design (nominal) is a function of the faith that also is colige the standard deviation of the product, using the following Equation and Figures 1, 2 and 4:

Equation 4.

$$f´CR = f´c + \sigma\ (k/cm^2)\ \text{See : } (^4)$$

If: Faith = so $A = \frac{\Delta f´cr}{\Delta C\ \%}$, then: $f´c = f\ (EF)$ and therefore the Equation 4 becomes:

Equation 5.

$$f´CR = f\ (EF) + \sigma\ (\text{ see})\ (\text{Figure 4}).$$

Where:

f´cr = Required average strength for a mixture (from dosage), (kg/cm^2).
Σ = Standard deviation of the mixture from the laboratory tests, (kg/cm^2).
FE = Effectiveness factor of the mixture, (kg/cm^2) (for every 1 % of cement).

Equation 5 reads as follows, if f´c is a function of FE, the problems of quality in the manufacture of concrete, represented by the Standard Deviation of the finished product, are all over f´c, (see Figure 4) and therefore, under the mathematical point of view, the concepts can be managed separately.

Important note: The FE is useful to obtain the percentage of cement needed for the mixture to achieve or exceed f´c. In other words, it theoretically is good for obtain the strength from zero to the maximum possible to be developed by concrete, in other words, corrects the problems of very high or very low strength.

3.3 Standard deviation of the mixture

It is important to know for each production plant, its "Real Effectiveness Factor", as a unique and intrinsic characteristic of it. Therefore, you can study the σ separately and some variables that affect it.

Table 3. Concept on the level of quality of the works According to the NTC 2275.

General construction tests (Concretes with greater than 210 kg/cm^2 strength)		
Standard Deviation	**Coefficient of Variation**	**Obtained Quality Level**
Less than 25	Less than 3.0	Excellent
Between 25 and 35	Between 3.0 and 4.0	Very good
Between 35 and 40	Between 4.0 and 5.0	Good

Between 40 and 50	Between 5.0 and 6.0	Acceptable
Greater than 50	Greater than 6.0	Poor

As shown in Table 4, there are too many variables to control, and in the case of the "poor quality level", should quantify each of them, to correct the problem. This is what proposes the control by processes, which all-classic methods conform. However, MD departs from this and focuses its study on the control of the finished product. Strength and Standard Deviation should be separated. If the production yields a poor concrete, you should study all the variables. If this is not the case, it is not necessary to do so. Knowing the production FE, the problem is easily corrected.

However, fortunately, experience has shown that to produce a concrete of acceptable quality is very easy. It is enough to control the weights of the materials and the puzzle is solved. It is necessary to establish new controls for the A/C such as those proposed by the MD in the paragraph 4.5 (see page www.cenaltec.com and paragraph 3.1). It is important to note that a constant A/C is not applicable in dry mixes because it depends on COHTT% and C% (see Equation 6 and paragraph 4.5.).

4. PREFABRICATION OF DRY MIXTURES VIBRO IMPACTED

Dry mixes are not tested by settlement because it would always give zero, in other words they do not compacted by themselves. For such a reason they require a vibrocompacting machinery to apply dynamic, static, vacuum and impact loads, which must be learned to handle.

Table 4. Variables that affect the standard deviation and the production of concrete.

HEAD OF THE CONCRETE	Budget.
	Enough information on site (drawings, mix dosage mixtures, permits etc.)
	Organization of the construction site and office.
BODY OF THE CONCRETE	Process control.
	Management of information from the laboratory tests (site, office and laboratory).
	Selection and sampling.
	Vibration and curing of concrete in the samples and on site.
	Internal and external transport of materials and mixes on site.
	Tests over materials and the mixes on site (sand, cement, slump, etc.)
	Variations in the quality of each material (standard deviation, σ_{mat}).
	Changes or combination of materials in the work by deficiencies in storage.
	Traceability of samples and materials.
	Management of "not conformities" of ISO 9001 standard, version 2000.
	Speed or time available to finish the work.
	Climate, additions and admixtures.
	Coefficient of Variation of tests and machinery.
MEMBERS OF THE CONCRETE	State of used machinery and equipment (controls and maintenance).
	Channels of communication in use (phones, cell phones, Internet, Web, etc.).
	Experience, instruction and training of the staff.

	Human errors and mistakes made of good or bad faith.
	People time availability.
	Malice of employees and workers.
	Continuity and employment stability of employees and workers.
	Interest of persons for the work, knowledge, power, etc.

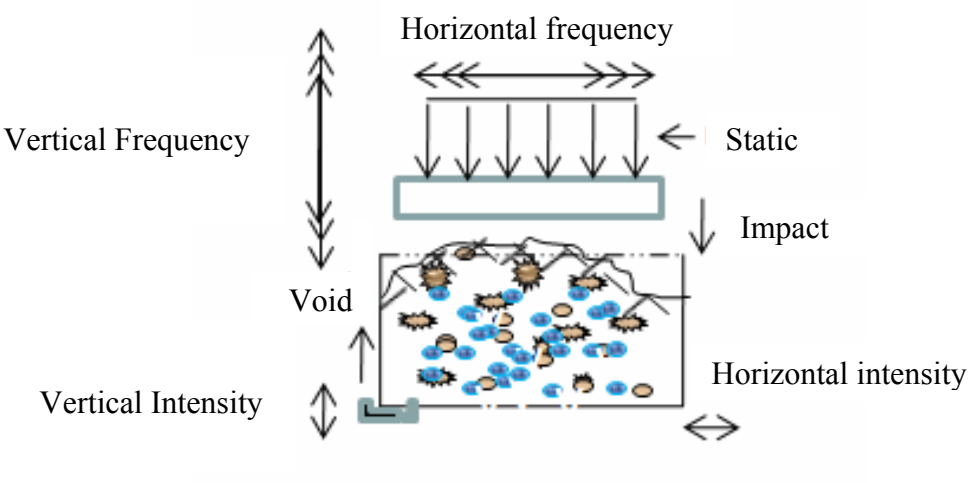

Figure 5. Applied energies during precasting.

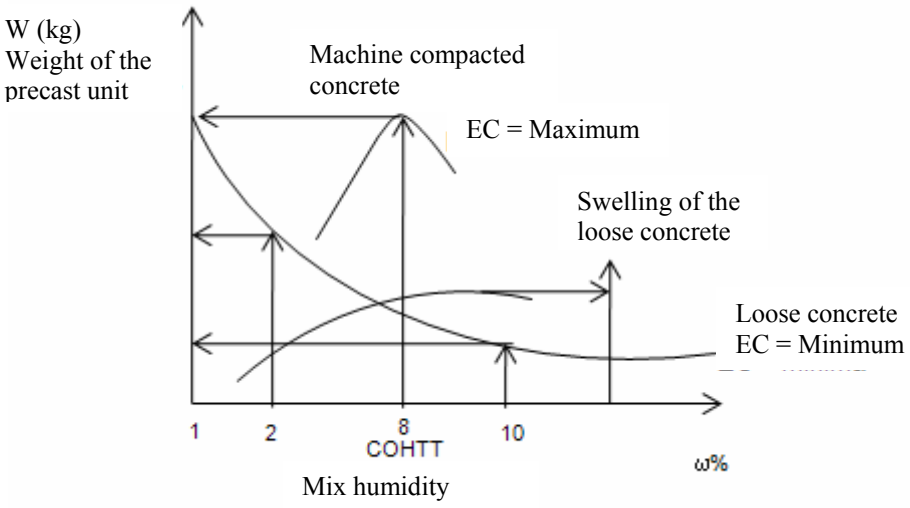

Figure 6. Weight of the precast unit vs. Compaction humidity.

Figure 5 shows the compaction mechanism used in the precasting process.

Figure 6 shows the mix of a precast piece compacted with zero (minimum)energy. The higher the humidity, the lower the weight of the material that will fit into the mold with the inevitable outcome of lowering the strength of the precast unit.

Figure 7 shows the variation of the amount of water that must be added to the mix, according to the energy developed by the machine. The EC1 < EC2 < EC3 < EC4 < EC5. Despite the fact that the EC1 < EC4, it was possible to introduce a greater amount of material in the mold with EC = 1 than in the mould with EC = 4 and this depends on the calibration of the machine.

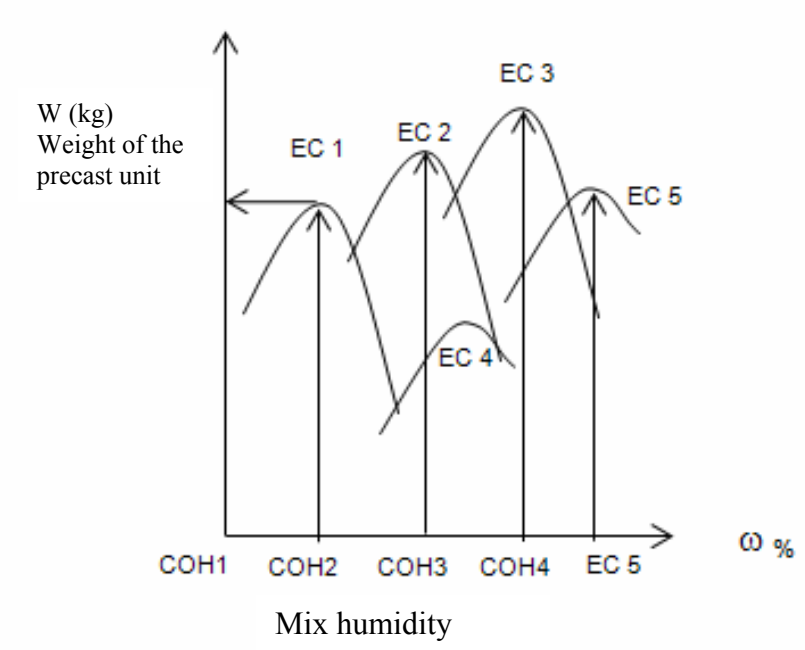

Figure 7. Variation of the weight of the precast compacted unit changing the applied energy and the humidity of the mix, with a constant C%.

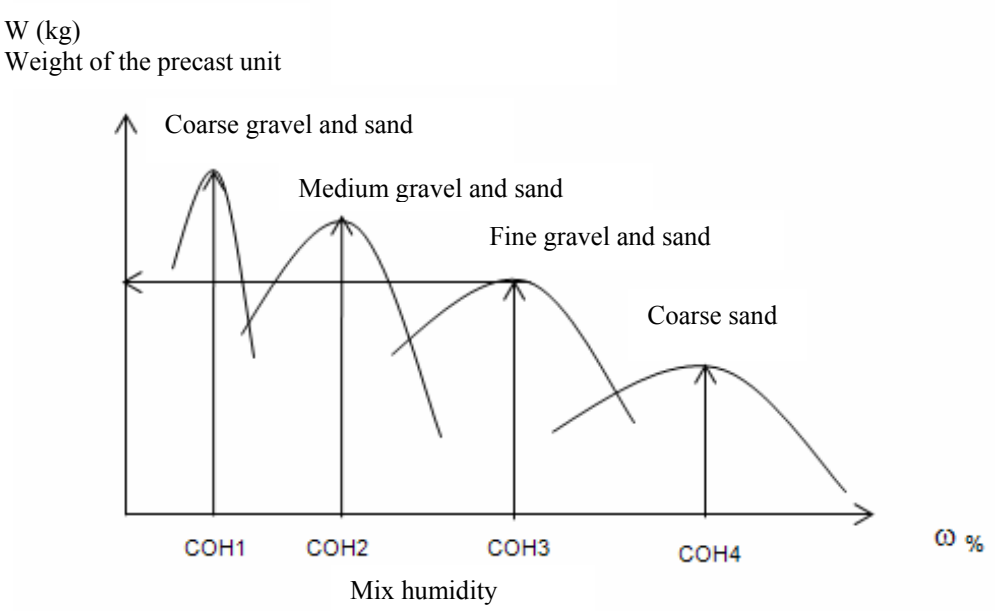

Figure 8. Variation of the weight of the precast compacted unit changing the skeleton and the humidity of the mix, C% constant.

Figure 8 shows the rising of the weight of the mixture of a precast unit proportionally to the dosage of the materials that make up the skeleton. It can be classified in rigid (open gradings with a lot of gravel) or flexible (closed gradings with very little gravel) ([5]) , taking into account than the sum of the percentages of sand and gravel is 100 % (see Equation 6).

Equation 6.

$$S\% + G\% = 100\%$$

Where:

S% = percent sand in the mix.
G% = percentage of gravel in the mix.

4.1 Machinery and material to use

There are two procedures.

- Conditioning the technical characteristics of the machine and the geometric charecteristics of the mold, to the type of material to be used. This situation would be very heavy, specially for the diversity of materials existing in nature.
- Conditioning the material to be used to the technical characteristics of the machine and the geometry of the mould. In such a case, the purpose is to find the Optimal Energy (EO) and the Optimum Dosage (DO), of the vibro-compacting machine, for it to conform to the conditions of the material to be used. This is achieved by trial and error, directly in the production of the precast unit, modifying the controls of the equipment, the way the mold is filled with the largest amount (weight) of the material, in the shortest possible time.

4.2 Correlation between the optimal moisture content of a mixture, the amount of cement required to obtain the required strength and the A/C relationship

The last thing to do done is to know the Optimal Moisture Content of the Mix for it to provide a good workability (COHT%) (see Figures 6 to 8). The pattern texture is achieved adjusting the distribution of the aggregate grading to the Fuller and Thompson curves. Other textures are achieved by changing the percentage of sand and therefore reducing the gravel. In this way the Optimal Moisture Content of the mix is defined to give the right workability and texture (COHTT%).

The way of controlling the A/C, departs from the concept that the dosage of the dry mixes is governed by the following equation, propose by the Author:

Equation 7.

$$COHTT\% = C\% \times A/C$$

In which C% is defined in the mathematical foundations of the MD. COHTT% is a "universal principle" that stablishes that the workability and the final texture of the concrete depend on the same nature of the mix. Therefore, the A/C relationship is a dependent variable of the two previous ones, C% and COHTT%.

Developing equation 7, Table 5 can be obtained.

Table 5. Water Cement Relationship (A/C) of a mix, as a function of the percentage of cement (C%) and the optimal moisture content (COHTT%).

(COHTT%) Optimal moisture content so mix reach the required workability and texture.	CEMENT PERCENTAGE (C%)	10%	15%	20%	25%	30%
		Water Cement Relationship of the mix (A/C)				
	2	0.20	0.13	0.10	0.08	0.07
	4	0.40	0.27	0.20	0.16	0.13
	6	0.60	0.40	0.30	0.24	0.20
	8	0.80	0.53	0.40	0.32	0.27
	10	1.00	0.67	0.50	0.40	0.33
	12	1.20	0.80	0.60	0.48	0.40

	14	1.40	0.93	0.70	0.56	0.47

5. CONCLUSIONS

- When using the MD, f´cr does not depend on the A/C, but it is a variable that depends on COH%, C% and the obtained σ in the production. In Figure 3 can be noted that it is possible to increase the strength of concrete, leaving the mixture´s A/C ratio as a constant. Also it is possible to increase the A/C, leaving his "third dimension" constant.
- The MD is excellent to dose all types of mixes used in construction as hydraulic concretes, joint mortars, grouting mortars, polymer concretes, asphalt concretes, and especially for dry mixes used for the precasting of blocks, pavers, layered tiles and concrete pavements, etc. It is very precise because it is a mathematical and statistical method, ideal for works with the ISO 9000, version 2000 quality management, and operating together with concrete producing plants, and allows its accreditation.
- The FE should be studied and know in a mixing plant to control and correct the defined dosages. It can easily be obtained by a testing laboratory and allows lowering the construction costs, without affect the quality of the finished product. The strength and the Standard Deviation should be separated. Knowing the production FE, it fixes the simultaneous problems of the strength and the low quality of the concrete.
- This work is an innovation because it provides new tools to handle the technical and budgetary areas in building engineering and because the mathematical and statistical fundaments, presented for the first time in this paper, improve the classic design methods or dosage of concrete and mortar mixes.
- It is essential to make a call to persons who are interested in continuing this work ahead since it is necessary to have personnel, ideas and resources to improve it every day.
- A new paradigm is born, a new approach called "*Software Hormigón*", a program that should be standardized, studied in the universities, applied in engineering works and considered in future research.

6. NOTES

(1) The dynamic method does not consider the absorption of aggregates, making easier the field and laboratory work (see pages www.cenaltec.com *or* www.policoncreto.com*., which explains how to correct the A/C relationship, for different mixes to the dry compacted ones).*

(2) Balancing Factor of a Mixture: Factor that balances the projected 28 day strength and the real 28 day strength of a concrete; it also balances the cement and concrete in a mixes producing plant.

(3) In Figure No. 3, W = workability varies from 1% to 10%. In wet, fluid slimy and liquid non-self-leveling, the patron workability is easy to define through the slump test. Water must be added to the mix up to the desired settlement and finally, the A/C relation is corrected (1).

In Figure No. 3, T% = Texture goes from 1% to 10%. The texture pattern is common to be defined by the adjustment of the grading curves to Fuller and Thompson curves.

(4) Standard deviation of the sample (σ)is mathematically obtained and must be affected by the probabilistic coefficients according with each case (NSR-98: C.5.3.1).

(5) The classification of the skeleton of the mix is not within the reach of this article.