A MIX DESIGN METHODOLOGY FOR CONCRETE BLOCK UNITS

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The use of concrete masonry units for high-rise load bearing construction has created a need for concrete block with high compressive strength. To achieve high strength levels, block producers generally define concrete mixtures by a trial and error process. The most common procedure is to produce some trial mixtures possessing different cement content using the equipment available in the block plant and test the strength of blocks. This approach is costly, time consuming and generally leads to expensive solutions for using large amounts of cement. Besides, it makes difficult to test new combinations of aggregates and admixtures once disturbs very much the plant routine. In this paper is presented a mix design procedure for structural concrete blocks based on laboratory tests. Initially a reference mixture is studied. In this phase it is possible to vary the type and proportion of aggregates, admixtures and water content in order to achieve a suitable face texture with lower energy of compaction. After that, several mixtures are produced varying the cement content and density. Cylindrical specimens was produced with these mixtures and tested in compressive strength. With the results, it is elaborated a mix design chart where the desired compressive strength can be obtained by varying the aggregate/binder ratio and density. The last phase is testing some selected mixtures in actual block machine, determining both density and compressive strength. With the results it is possible to make the final adjustments in the mix proportions. The application of this procedure in a block plant of the south of Brazil led to satisfactory results showing that is possible to forecast of the mechanical resistance of the concrete blocks starting from laboratory studies in cylindrical specimens and also demonstrated the importance of the control of several parameters related to the productive process for the compressive strength of the units.

Keywords: *mix design, concrete block, dry concrete, vibrocompression machines*

INTRODUCTION

The production of concrete blocks used in both structural and cladding masonry is characterized by the use of "dry concrete". This special type of concrete has significantly greater consistency than conventional plastic concrete due to its lower water content, which is required to push the blocks out of the molds immediately after forming (MARCHAND, 1996). This characteristic makes the use of vibrocompression machines necessary; these are special compaction devices that simultaneously apply compression and vibration to eliminate air voids when molding the blocks. The properties of this particular type of concrete do not depend exclusively on the water: cement ratio and are rather influenced by the size and type of vibrocompression machine employed. Hence, the existing mix design methods for this type of concrete require excessively arduous, expensive, and time consuming tests in concrete plants. The most used methods are those disseminated by the largest machine manufacturers.

For example, Besser Company recommends a method developed by Pfeifenberger (1985), which relies on the adjustment of the grading curves of available aggregates. Columbia, another American company, recommends a different method based on the studies carried out by Wilk & Grant (1948) and by Menzel (1934). This method, which also relies on the plotting of an ideal aggregate grading curve, takes into account mixture fine content – including the amount of cement – in order to achieve the minimal cohesion necessary to mold the blocks. In Brazil, Medeiros (1993), Tango (1994) and Ferreira (1995) have also made important contributions to the development of mix design methods for this type of concrete. However the above-mentioned methods not only require excessive tests in plants using vibrocompression machines, but they also fail to consider certain peculiarities and characteristics of the concrete block production process when determining the mixtures to be tested. Frasson Jr. (2000) developed a method aiming to reduce the number of tests in industrial settings, which makes mix design faster and less expensive. In addition, this method takes into account several parameters that are important for both process performance and product quality when defining the mixtures to be tested in industrial settings.

Frasson’s method is based on the molding of (2x4 in) cylindrical concrete specimens in laboratory. With these specimens, it is possible to evaluate the cohesion and optimal water content of the mixtures, as well as predict block surface texture and compressive strength, the latter being a function of density in the fresh state. This method is described in the following section and its application in a mix design case study is presented.

THE MIX DESIGN METHOD

CHOICE AND RATIO OF AGGREGATES

The coarse aggregates most employed in concrete block production are those that pass through a 3/8 in (9.5 mm) sieve and are retained by a number 4 (4.8 mm) sieve. Preferably, the aggregate particles’ shape must be cubic, which allows use of larger amounts in concrete mixtures without altering the block’s surface texture. To ensure adequate cohesion of the mix, the fine aggregate (or mixture of fine aggregates) must have a fineness modulus of 2.20 to 2.80 and the percentage of fine aggregate that passes through a number 50 (0.3 mm) sieve must be between 25 and 35 %.

The proportion of coarse aggregate (with respect to total aggregates) should be within a range of 20 to 40 %. Moreover, the exact proportion must be defined experimentally, taking into account both the surface texture and cohesion of the concrete. This should be done by molding 2x4 in (5x10 cm) specimens composed of a 1:9 (cement: aggregate) mixture with different coarse aggregate: total aggregate ratios varying from 10 to 50 %, by 10 % intervals. The most suitable ratio is that which allows the mixture to satisfy requirements of cohesion and texture, but also that which contains the largest possible amount of coarse aggregate. In the industrial market, surface texture is a characteristic often influenced by consumer perception, although there is a tendency to produce coarser textures for structural blocks – especially for those with elevated compressive strength (F_{bk} > 1305 psi – 9.0 N/mm^2) – and finer textures for cladding blocks.

As mentioned above, in addition to evaluating the texture of the mixtures, cohesion tests must also be carried out (following the procedure presented below). With respect to mixture cohesion, the smaller the amount of cement in the mixture, the less cohesive it will be. Mixtures with small amounts of cement are involved in the production of blocks used for cladding. Hence, following the determination of the ideal proportions of coarse and fine aggregates using a cement: aggregate ratio of 1:9, it is recommended that more tests be performed on mixtures with lower ratios (1:13 to 1:15) to evaluate cohesion in these critical cases. It is worth emphasizing that the density value determined for the molding of the specimens will greatly influence both their texture and cohesion. For this reason, the present method refers to a density of 131.09 lb/ft^3 (2100 kg/m^3), which is very close to the average density of concrete blocks obtained with the use of the best vibrocompression machines available.

EVALUATION OF COHESION AND SURFACE TEXTURE

As mentioned, the mix-design methodology proposed here is based entirely on the molding of 2x4 in (5x10 cm) cylindrical specimens, using a 2x5.2 in (5x13 cm) tri-panel mold (see Figure. 1). In addition to the mold itself (made of three curved side panels held together by a brace), the molding equipment is comprised of a metallic base measuring 2.76 in (7 cm) in diameter by 0.79 in (2 cm) in height, a compacting bar normally used for compacting mortar (the dimensions of which follow the recommendations of the ABNT - NBR 7215 Brazilian standard, 1996), a plastic funnel, a nylon tamper, and a rubber hammer (see Figure 1b).


(a) (b)

Figure 1: Equipment used for molding the 2x4 in specimens: a) 2x5.2 in cylindrical tri-panel mold; b) complete set of molding equipment

Figure 2 illustrates the sequence in which the 2x4 in (5x10 cm) specimens are molded. To mold the specimens, one must first weigh the materials in order to obtain concrete with the desired density after compacting. The total mass of material placed in the tri-panel mold is then divided into four equal parts so that molding can be carried out with four identical layers. The first layer is put into the mold and receives twenty strokes with the mortar compacting bar. Then the next layer is placed into the mold over the first one, receives twenty more strokes, and so on. The energy applied with the compacting bar strokes must be distributed equally among each layer in such a manner that the specimen's height be between 4.06 in and

4.13 in (10.3 cm and 10.5 cm) after the 80 compacting bar strokes. The specimen's final height of 3.94 in (10 cm) will only be achieved after additional strokes are applied to it with the rubber hammer and nylon tamper. Finally, the brace holding the mold's three panels is unscrewed in order to unmold the specimen.

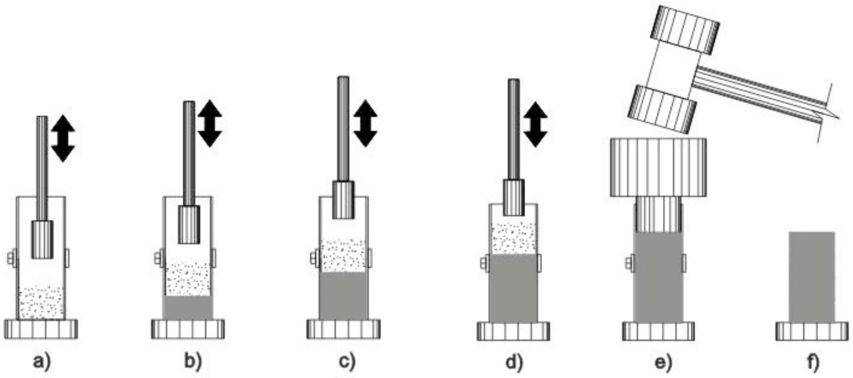

Figure 2: Schematic of the 2x4 in specimen molding sequence: a) Compacting of the 1st layer; b) Compacting of the 2nd layer; c) Compacting of the 3rd layer; d) Compacting of the 4th layer; e) Compacting the remaining 3 mm with the rubber hammer and nylon tamper; f) Unmolding of the specimen.

The state of the surface of recently molded specimens is an excellent predictor of the final surface texture obtained when the mixture is used in industrial settings. The assessment of the specimen's surface is carried out during the phase in which ideal proportions for the aggregates are determined. The texture of the specimens must be visually assessed for each type of mixture, at optimum water content and for a density of 131.09 lb/ft^3 (2100 kg/m^3).

To determine the optimum water content of a mixture for a given degree of compacting and surface texture, one need only assess the state of the specimen's surface following its removal from the mold. Much as occurs in industrial settings, when the mixture's water content approaches the optimal value, the specimen's surface will start becoming slightly humid (see Figure 3a). Moreover, the internal surfaces of the mold and of the metallic base, used as support during the molding, will also become slightly humid (see Figure 3b and 3c).

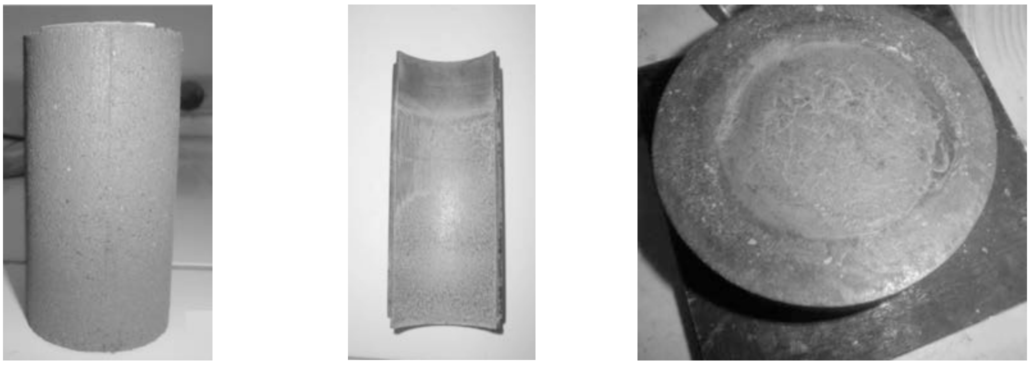
a) b) c)

Figure 3: Indication of optimum water content for a mixture: a) specimens recently removed from molds and presenting slight traces of humidity; b) surface of the mold made slightly humid by the cement paste; c) molding base slightly wet from the cement paste.

Mixtures with moisture content below this point will require more energy to be compacted, which will mean losses in productivity and more wear on the vibrocompression machinery. Values above this point can make it more difficult or even impossible to produce concrete blocks due to problems relating to block deformation occurring during removal from the mold, and to adherence to the mold itself.

The fresh mixture’s cohesion can be determined by compressing recently molded specimens along their diameter (the specimens must have optimum moisture content and texture). The procedure is as follows. Two specimens are placed on a horizontal surface, parallel to one another, with a distance of 11.81 in (30 cm) separating their axes. A plane wood board measuring 19.69x7.87 in (50x20 cm) and with a minimum thickness of 0.59 in (1.5 cm) is laid on top of the specimens for load transfer purposes. A container is placed on top of the board and filled with enough water to exert a uniform load of 2.20 lb/s (1 kg/s) on the specimens. The test aims to determine the load that is necessary to crush the specimens (see Figure 4).

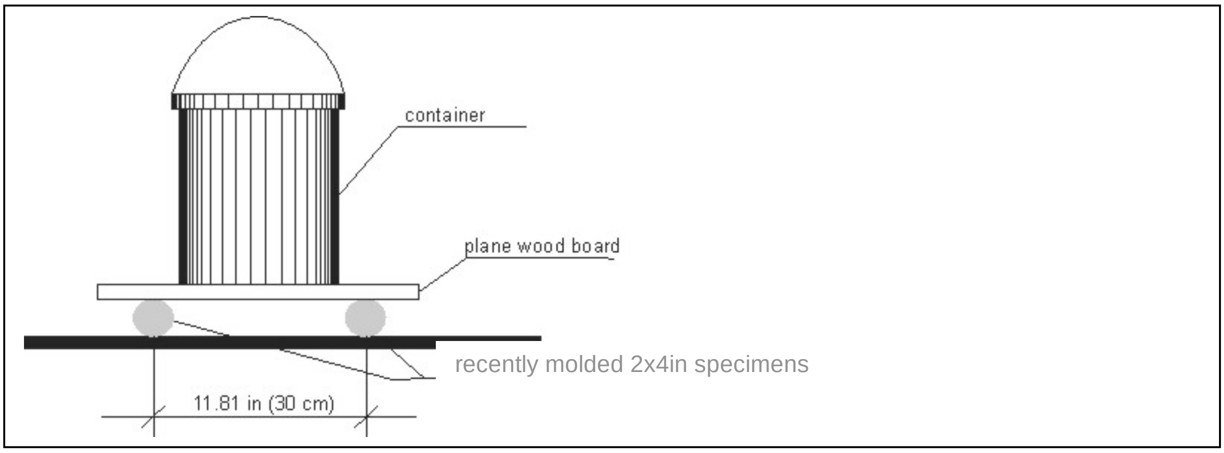

Figure 4: Determination of the fresh mixture’s cohesion

To ensure adequate cohesion, the recommendation is that specimens should tolerate a load of 11.02 to 17.64 lb (5 to 8 kg). Let us emphasize that this minimum value does depend on the production process, and mainly on the part of the process concerned with the transport of fresh blocks (e.g., manual transport vs. use of a pallet transporter system).

PREPARATION OF MIXTURES TO PLOT A MIX DESIGN CURVE

Determining what density value should be used in the mix design study is a difficult task that depends on the vibrocompression equipment employed and on its settings. We therefore suggest that one use a range of density values that covers those normally obtained in industrial settings. Three values (minimum, average, and maximum density) falling between 121.73 and 140.47 lb/ft^3 (1.95 and 2.25 kg/dm^3) can be employed for laboratory studies.

The use of the following cement: aggregate ratios is suggested to check the influence of the amount of cement included in the mixture: 1:7, 1:9, and 1:11; these ratios are common in production of structural concrete blocks with a compressive strength of 652.70 to 1740.54 psi (4.5 to 12 MPa). For each ratio and amount used in the mix design study, the optimum moisture content should be determined following the procedure described in previous section.

Subsequently, four 2x4 in (5x10 cm) specimens should be molded so that their compressive strength can be evaluated after 28 days.

It is worth noting that when the mix design study is conducted in laboratory, curing should be carried out in polystyrene foam cases with a sheet of water at the bottom of the case. If the mix design methodology is applied in the concrete block plant, then the curing process used for the specimens should be the same as the one used in the plant (e.g., atmospheric pressure method, low-pressure curing, high-pressure steam curing).

ESTIMATE OF AVERAGE COMPRESSIVE STRENGTH AS A FUNCTION OF SPECIFIED COMPRESSIVE STRENGTH

In case coefficient of variation values for compressive strength are unavailable for the plant concerned by the mix design study, coefficient of variation values are suggested below in Table 1. These values vary with the type of proportioning (mass, flux, or volume), with the equipment that is available, with the production control process, and with the experience of the production staff.

Once the values for each item in Table 1 are defined, an average of the appropriate values can be calculated to determine the coefficient of variation used in Equation (1):

$$F_{bm} = \frac{F_{bk}}{(1 - 1.65.CV)} \qquad (1)$$

Where: F_{bm} = Average compressive strength of the cement blocks (considering the gross area) at a given age;
F_{bk} = specified compressive strength at a given age;
CV = Coefficient of variation

Table 1: Production condition/type of control scales for estimating the coefficient of variation for a given cement plant

Type of control / machines	Coefficient of variation (%) values, depending on production conditions		
	Good	Average	Poor
1 – Control of process and experience of the production staff	5	15	25
2 – Machines: vibrocompression and humidity sensors	5	15	25
3 – Batching by volume	5	10	15
4 – Batching by mass	10	15	20

DETERMINATION OF THE CEMENT: AGGREGATE RATIO

With the compressive strength results for the 2x4 in (5x10 cm) specimens, compressive strength versus density curves are plotted for each cement: aggregate ratio used (see Figure 5 near the end of this article).

By first determining the density of the concrete blocks produced with the vibrocompression machine that will be used in actual production, and with the compressive strength versus density curves presented in Figure 5, we can ascertain compressive strength of the 2x4 in (5x10 cm) specimens for each cement: aggregate ratio. With the compressive strength of the specimens, one can predict the average compressive strength (F_{bm}) of the cement blocks, using Equation (2):

$$F_{bm} = \frac{f_s}{0.8} \cdot \frac{A_{net}}{A_{gross.}} \qquad (2)$$

Where: f_s = Average compressive strength of the 2x4 in specimens;
A_{net} = Net area of the cement blocks;
$A_{gross.}$ = Gross area of the cement blocks;

The *specimen vs. block* coefficient for blocks measuring (5.51x 7.48x 15.35) in is 0.8 (see Frasson, 2000)

With the desired compressive strength, one can determine the cement: aggregate ratio to be used in industrial settings while allowing for eventual fine-tuning at the cement plant.

APPLICATION OF THE MIX DESIGN METHODOLOGY: A CASE STUDY

Below, a case study of the application of the proposed methodology is presented. In this case, the methodology was applied by a vibrocompressed block manufacturer located in the Greater Florianopolis area (in southern Brazil).

MATERIALS

The cement used by the manufacturer and in the mix design study was high early strength Portland cement (CP V – ARI, per the NBR 5733 Brazilian standard, 1991). Three aggregates were employed: one coarse granite aggregate (with a fineness modulus of 5.65) and two fine aggregates (coarse sand and fine sand with respective fineness modulus of 2.84 and 0.94).

PROPORTIONS FOR THE VARIOUS AGGREGATES

Through preliminary tests carried out by molding 2x4 in (5x10 cm) cylindrical specimens – using a test ratio of 1:9 (cement: aggregate) as well as a density of 131.09 lb/ft^3 (2100 kg/m^3) – and the evaluation of the specimen's surface texture and cohesion, the following aggregate proportions were determined: 30 % coarse aggregate, 47 % coarse sand, and 23 % fine sand.

It should be emphasized that the fineness modulus of the combined fine aggregates (coarse and fine sands) was 2.22. An aggregate mix with a fineness modulus nearer to the lower boundary recommended in previous section was chosen due to the lack of fine particles in the coarse sand and to low cohesion of the mixtures when aggregate compositions with larger particles are used.

MOLDING OF 2X4 IN SPECIMENS TO PLOT MIX DESIGN CURVES

To mold the specimens, three different cement: aggregate ratios were used (1:7; 1:9; 1:11) with the aggregate proportions mentioned just above. The proportions in mass used for the mixtures are presented below in Table 2.

Table 2: Mix proportions in mass

Cement: aggregate ratio	Materials			
	Cement	Coarse aggregate	Coarse sand	Fine sand
1:11	1.00	3.30	5.17	2.53
1:9	1.00	2.70	4.23	2.07
1:7	1.00	2.10	3.29	1.61

As can be seen in Table 3, for each mixture three different densities (in fresh state) were tested. Cohesion and optimal water content for specimen molding were determined for all nine combinations of ratio and density. Moreover, for each ratio-density combination, four 2x4 in (5x10 cm) specimens were molded so as to determine their compressive strength after 28 days. Curing was conducted in a polystyrene foam case with a sheet of water at the bottom of the case.

Table 3: Cohesion and optimal water content of mixtures for the various ratios and densities tested

Cement: aggregate ratio	Density (kg/m^3)	Optimal water content[1] (%)	Cohesion (kg)
1:11	131.10 lb/ft^3 (2100)	6.86	8.07 lb (3.66)
	136.10 lb/ft^3 (2180)		12.30 lb (5.58)
	140.47 lb/ft^3 (2250)		20.24 lb (9.18)
1:9	132.98 lb/ft^3 (2130)	6.83	8.62 lb (3.91)
	137.35 lb/ft^3 (2200)		17.33 lb (7.86)
	142.34 lb/ft^3 (2280)		26.57 lb (12.05)
1:7	134.22 lb/ft^3 (2150)	6.95	10.32 lb (4.68)
	139.22 lb/ft^3 (2230)		11.86 lb (5.38)
	143.59 lb/ft^3 (2300)		25.26 lb (11.46)

1 – In this mix design methodology, the mixture water content is equivalent to the water: dry materials ratio.

Table 4 presents results for specimen compressive strength after 28 days. It should be mentioned that the specimens were capped with a thin layer of cement and sulfur paste before the compressive strength test. The mix design curves in Figure 5 were plotted using results from Table 4.

Table 4: Specimen compressive strength

Cement: aggregate ratio	Density (kg/dm^3)	Average Compressive Strength (MPa)	Standard deviation (MPa)
1:11	131.10 lb/ft^3 (2100)	1726.04 psi (11.90)	281.39 psi (1.94)
	136.10 lb/ft^3 (2180)	2211.94 psi (15.25)	250.93 psi (1.73)
	140.47 lb/ft^3 (2250)	2800.82 psi (19.31)	252.38 psi (1.74)
1:9	132.98 lb/ft^3 (2130)	2342.48 psi (16.15)	120.39 psi (0.83)
	137.35 lb/ft^3 (2200)	3186.64 psi (21.97)	127.64 psi (0.88)
	142.34 lb/ft^3 (2280)	3788.57 psi (26.12)	391.62 psi (2.70)
1:7	134.22 lb/ft^3 (2150)	2863.19 psi (19.74)	219.02 psi (1.51)
	139.22 lb/ft^3 (2230)	3626.12 psi (25.00)	127.64 psi (0.88)
	143.59 lb/ft^3 (2300)	4177.30 psi (28.80)	583.08 psi (4.02)

ESTIMATE FOR THE AVERAGE COMPRESSIVE STRENGTH OF THE BLOCKS AS A FUNCTION OF THE SPECIFIED COMPRESSIVE STRENGTH

This mix design study was developed to determine a cement: aggregate ratio allowing the production of concrete blocks with a specified compressive strength of 1740.45 psi (12.0 MPa). Based on the values in Table 1, an average coefficient of variation equal to 10% was obtained. With this estimate, one can determine the estimated average compressive strength of the cement blocks, by setting F_{bk}=1740.45 psi (12.0 MPa) (the specified compressive strength of the blocks considering the gross area).

$$F_{bm} = \frac{F_{bk}}{(1-1.65.CV)} = \frac{1740.54}{(1-1.65*0.10)} = 2084.48\,psi\ (14.4\,MPa) \qquad (3)$$

The cement block that was produced measured 5.51x 7.48x 15.35 in (14x 19x 39 cm) and its net area/gross area ratio was 66.8 %. With these data and the block's average compressive strength, the specimens' average compressive strength can be calculated using Equation 2.

$$F_{bm} = \frac{f_s}{0.8}.\frac{A_{net}}{A_{gross}} \Rightarrow f_s = \frac{F_{bm}*0.80}{(A_{net}/A_{gross})} = \frac{2084.48*0.80}{0.668} = 2496.38\ psi\ (17.2\ MPa) \qquad (4)$$

In order to use the mix design curves presented in Figure 5, we evaluated the capacity of the vibrocompression equipment (an MBX 975 - Montana vibrocompression machine manufactured by Trillor Máquinas, a Brazilian company) to compact concrete blocks. To do so, a mixture with a 1:9 cement: aggregate ratio was prepared with the vibrocompression machine, in industrial settings, using the aforementioned aggregate composition.

Concrete blocks were produced with this medium cement: aggregate ratio (1:9) and with the in-production water content adjusted to values near optimal water content; feeding time was adjusted so that vibrocompression duration (i.e., time needed to vibrocompress the blocks) could be around 5 to 7 seconds. The density of a series of 12 blocks in fresh state was assessed: the average density was 134.22 lb/ft^3 (2150 kg/m^3).

Looking at the chart in Figure 5, with the value just mentioned for average density and an average compressive strength equal to 2496.38 psi (17.2 MPa), it can be seen that the cement: aggregate ratio required for the production of blocks characterized by an F_{bk} equal to 1740.45 psi (12.0 MPa) is very close to 1:9.

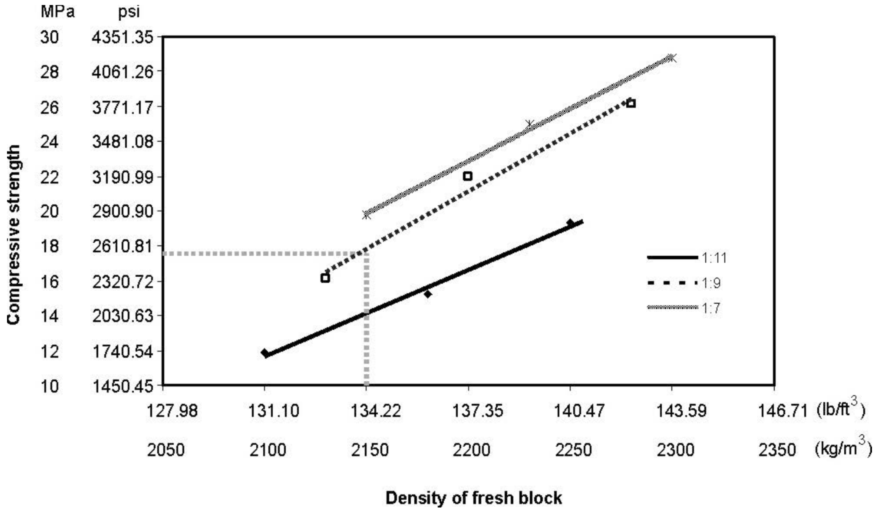

Figure 5: Determination of the cement: aggregate ratio necessary for the production of concrete blocks with an F_{bk} equal to 1740.45 psi (12.0 MPa).

To evaluate the compressive strength of the blocks after 28 days, a sample of 8 blocks was taken from the set of blocks that were produced in the plant and underwent heat curing. Table 6 presents results for the compressive strength of these 8 blocks.

Table 6: Compressive strength of 8 blocks produced in the plant

Block	Compressive strength (MPa)		Standard Deviation (MPa)	Average compressive strength – gross area (MPa)
	Net area	Gross area		
01	3285.27 psi (22.65)	2194.53 psi (15.13)	100,08 psi (0.69)	2074.14 psi (14.3)
02	3082.21 psi (21.25)	2059.64 psi (14.20)		
03	3105.41 psi (21.41)	2074.14 psi (14.30)		
04	2863.19 psi (19.74)	1913.14 psi (13.19)		
05	3195.34 psi (22.03)	2135.06 psi (14.72)		
06	3002.43 psi (20.70)	2005.97 psi (13.83)		
07	3016.94 psi (20.80)	2014.67 psi (13.89)		
08	3305.57 psi (22.79)	2207.58 psi (15.22)		

As can be seen in Table 6, that the average compressive strength obtained was similar with the estimate (14,44 MPa).

CONCLUSION

The mix design method proposed by Frasson (2000) and presented here is a significant contribution with respect to the production of vibrocompressed concrete blocks. It is a simple and practical method that does not require excessive tests with vibrocompression equipment. This makes it appealing from an economic standpoint. In addition, it establishes new concepts and new tests for the evaluation of the properties of dry concrete: the cohesion of mixtures in fresh state; the determination of optimal water content of mixtures; the prediction of their surface texture; and the relationship between the block’s degree of compacting and compressive strength, which makes it possible to precisely predict the latter (regardless of the vibrocompression equipment’s capacity) by molding 2x4 in (5x10 cm) specimens.

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