ELSEVIER

Cement & Concrete Composites 26 (2004) 613–621

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

A comparison of mix proportioning methods for high-strength concrete

M.F. Alves, R.A. Cremonini *, D.C.C. Dal Molin

Universidade Federal do Rio Grande do Sul, Escola de Engenharia, Departamento de Engenharia Civil/NORIE, Av. Osvaldo Aranha, 99 Porto Alegre 90035-190, RS, Brazil

Received 2 July 2001; accepted 3 February 2003

Abstract

The use of high-strength concrete (HSC) has increased all over the world. Among the factors that justify this increased use is the strength increase for structural aspects and durability. The production of this material results in large consumption of natural sources and energy, as, in general, it is characterized by larger consumption of cement, when compared to the conventional concretes (compressive strength $\leqslant 50$ MPa). In Brazil, little emphasis has been given to the HSC mix proportioning methods, for their use is not common practice in the construction industry yet, the production of HSCs being achieved through proportioning methods used for conventional strength concretes. The use of these methods, besides presenting technical difficulties, also generates high cement consumption, large consumption of energy and high consumption of raw materials in general. For the present study four proportioning methods were selected, one being for conventional concrete and three specifically for high strength. The resulting concretes are compared for compressive strength, cement consumption and economic viability. The results obtained indicate the advantage of using specific proportioning methods for HSC, as for the same compressive strength at 28 days, savings up to 50% in the consumption of cement were achieved, which represents a significant reduction of energy, raw material consumption and costs.

Keywords: High-strength concrete; Mix proportioning; Compressive strength; Cement consumption; Concrete industry; High performance

1. Introduction

For many decades, concrete has been largely used as a construction material, whether in moderate aggressive environments, or in strongly aggressive environments. This is due to the fact that it possesses excellent water resistance, can be moulded in a variety of shapes and sizes, and for being cheaper and more easily available in the field. To illustrate such statement, Mehta and Monteiro [1] estimated that the world consumption of concrete reaches the order of 5.5 billion tonnes a year.

Besides the aspects mentioned above, the use of concrete as structural material is favoured by its mechanical properties, mainly compressive strength, a very significant parameter for design engineers and for those who perform quality control. This property is highly important for characterizing the material, serving as reference for its classification. The advance of concrete technology, as well as the development of new materials and components have resulted in increased performance and strength needs, which were not being adequately satisfied any longer. Material degradation, the bad condition of structures in the long term and the large demand of new architectural forms have accelerated research on concrete microstructure, generating the need to elaborate new codes and standards.

The satisfactory performance of structures, in the long term, has become vital for the economy of all nations. In that context, concrete has been the largest provider of stable and reliable structures, since the Greek and Roman civilization [2]. In what concerns durability, Mehta [3] explains that the low water/cement ratios used in the manufacture of high-strength concrete (HSC) already guarantee that durability requirements, such as low permeability, are already being considered.

Although presently there are already parameters and mixing criteria for the production of HSC, the materials and their corresponding proportions are still chosen empirically through extensive laboratory testing.

* Corresponding author. Fax: +55-51-3316-9999.
E-mail address: rac@ufrgs.br (R.A. Cremonini).

0958-9465/$ - see front matter
doi:10.1016/S0958-9465(03)00036-2

Consequently, HSC ends up being produced using mixing methods of conventional concretes, as the proportioning methods specifically developed for HSC are few [4]. HSC mixes are generally characterized by low water/binder ratios, high consumption of cement, and the presence of various chemical and mineral admixtures [5]. In accordance with Domone and Soutsos [6], the optimization of the material proportions is harder for HSC than for conventional concrete. Besides, many existing proportioning methods for concrete are based on data and knowledge of existing materials in a specific region or country, and generally are restricted to Portland cement, aggregates and water. These methods are not adequate for the optimization of the many factors that must be considered for mixing HSC. HSC, incorporating mineral and chemical admixtures, presents a complex internal structure, which makes the use and the extrapolation of the classic proportioning methods difficult, particularly, due to the following aspects: compatibility between the admixture and binder, low water/cement or water/cementitious materials ratio, and the efficiency of the admixture in relation to the batching sequence as well as to the loss of properties with time [7].

2. Experimental programme

In order to verify the influence of the different mixing methods on the production of HSC, an analysis of the various mixing methods was made, from which four were chosen to be executed in accordance with the criteria of practicability, costs, material consumption and technical feasibility. The present study is based, among other characteristics, on cement consumption and the cost per cubic meter of concrete; other analysis can be found in [8].

The objective of any proportioning method is to determine an adequate and economic rate for the materials making-up the concrete, which can be used in its production, giving as close as possible the desired properties, with the lowest cost [9]. The chosen proportioning methods for this research were the IPT/EPUSP method [10], the Mehta/Aitcin method [11], the Toralles Carbonari method [12], and the Aitcin method [9]. This choice having been made following some efficiency criteria, fundamental principles and technical limitations of each method. A brief description of each method is presented.

IPT/EPUSP method [10]: The IPT/EPUSP method was selected for being widely used in Brazil. Besides, it is easy to apply, and can be executed in the field, without the need of special testing laboratory. *Main principles:* It is based on experimental determinations to establish the dry-mortar ratio (corresponds to the ratio between cement and fine aggregates relating to cement, fine and coarse aggregates by mass) and the water amount to given workability measured by slump test.

- It is possible to build a "Proportioning Diagram" for each mix and modelling concrete's behaviour considering aspects such as compressive strength, water/cement ratio, aggregates/cement ratio and cement content per cubic meter.

Step-by-step:

(a) Minimum cementitious material content determination: Its necessary to define a minimum cementitious material content, capable to give a desirable workability. To do so, it is necessary to determine the optimum dry-mortar ratio. Initially one trial batch is prepared and variations in the materials proportions are done, evaluating the workability and practical observations.
(b) After the optimum dry-mortar ratio and water amount are established at least two other batches are prepared. One with higher and other with smaller cement consumption and the same workability and mortar ratio.
(c) Specimens are moulded for testing at the required ages, thus enabling the correlation of strength X water/cement ratio; water/cement ratio X dry aggregates (m) and aggregates X cement consumption.

Metha/Aitcin method [11]: The Mehta/Aitcin method was chosen due to its easy development and execution. It is a practical method which can be applied in the field.

Main principles:

(a) For HPC, it seems that 35% cement paste by volume represents an optimum solution in balancing the conflicting requirements of strength, workability, and dimensional stability.
(b) The slump and maximum size aggregate (MSA) are not necessary for consideration since slump can be controlled by the superplasticizer dosage.
(c) Mineral admixtures are necessary to obtain technical benefits.
(d) The optimum proportion between fine aggregate and coarse aggregate is 65% by volume.

Step-by-step: Estimation of mixing water: based on experience with high-slump superplasticized concrete mixtures containing 12–19 mm MSA.

(a) Volume fraction of cement paste components: considering that the total volume of cement paste is 0.35 and it contains 0.02 of entrapped air, there are three options: Portland cement (PC) alone; PC + fly ash (FA) or blast furnace slag (BFS); and PC + FA + condensed silica fume.

(b) Estimation of aggregate content: from the total aggregate volume (0.65), assume a 2:3 volumetric ratio between fine and coarse aggregate for grade A (lowest strength).
(c) Calculation of batch weights: the mix proportions for the first trial batch are calculated considering the specific gravity values for normal PC, FA, BFS, silica fume and aggregates.
(d) Superplasticizer dosage: start with 1% superplasticizer (on anhydrous solid basis) by weight of cementitious materials.
(e) Trial batch adjustment: due to the assumptions underlying the proposed method, the calculated mix proportions for the first trial batch serve only as a guide. Several laboratory trials using the actual materials may be required before one arrives at the right combination of materials and mix proportions which satisfy the given criteria of workability and strength.

Toralles Carbonari method [12]: The Toralles Carbonari method was developed by a Brazilian researcher. *Main principles:* The main idea concerning this method is that HSC can be produced by optimizing, in separate, the cementitious materials and the aggregates, and reaching the best mix of both.

- There is an ideal mix of fine and coarse aggregates that contains the minimum void content. To this mix should be added an amount of binder, higher than the minimum void content, called cementitious materials excess.

Step-by-step: Cementitious materials optimization: it is necessary to determinate a water/cement + admixture ratio and estimates the superplasticizer saturation point.

(a) Fine and coarse aggregates optimization: it is necessary to find the fine and coarse aggregate's mix which presents the minimum void content. To do so, the dry rodded unit weight is determined.
(b) Cementitious materials and aggregates mix: several different combinations of cementitious materials contents and aggregate's mixes are made, starting from excess zero (binder content = voids content) up to 10% of binder excess. Test specimens produced through different combinations of cementitious materials and aggregates mixes are tested for compressive strength to define the combination which gives the desired compressive strength with a desired workability.

Aitcin method [9]: The Aitcin method was chosen as an evolution of an already existing method (Mehta/Aitcin method) which the authors have possibly improved, and made modifications considered necessary to the initial method.

Main principles:

- Follows the same approach of ACI 2111 Standard Practice for Selecting Proportions for normal, heavyweight and mass Concrete (1989) and it is a combination of empirical results and mathematical calculations based on the absolute volume method.

Step-by-step:

(a) A suggestion of water/cementitious materials ratio can be found by a nomogram (from 40 to 160 MPa at 28 days).
(b) Estimation of minimum water dosage, according to the superplasticizer saturation point.
(c) The superplasticizer dosage can be deduced from the dosage at the saturation point. If the saturation point is not known, it is suggested to start with a trial dosage of 1.0%.
(d) The coarse aggregate content can be found according to its shape.
(e) The authors suggest using 1.5% as an initial estimate of entrapped air content, and then adjusting it on the basis of the result obtained with the trial mix.
(f) A Mix Design Sheet is presented and should be completed in order to calculate the mix proportion of the materials and establish the first trial batch proportions.

2.1. Planning of tests

For each proportioning method, a minimum of four concrete batches were defined in order to enable to draw the Abrams Curve. It was based on a sample size analysis to check the number of repetitions needed for each batch, three repetitions were established for each batch executed by the IPT/EPUSP and the Toralles Carbonari methods, and two for the other two methods.

2.2. Materials

The present study involved the use of the following materials:

- High initial strength Portland cement (density = 3.11 kg/dm^3). Main characteristics of the cement are given in Table 1;
- coarse aggregate consisting of basalt crushed stone with 19 mm maximum size (MSA) and density = 3.06 kg/dm^3;
- fine aggregate consisting of natural river sand with a fineness modulus of 2.42 and density = 2.63 kg/dm^3;
- silica fume with density = 2.22 kg/dm^3 and specific surface determinated by nitrogen absorption = 1420 m^2/kg. Main characteristics of the silica fume are given in Table 2.
- sulphonated naphthalene superplasticizer with density = 1.24 kg/dm^3 and 40% solids content.

Table 1
Characteristics of cement

Characteristics	Properties	
Chemical	Ignition loss	2.13%
	MgO	1.51%
	SO_3	3.27%
	Na_2O	0.08%
	K_2O	0.89%
	CaO	0.98%
	C_3S	59.92%
	C_2S	11.79%
	C_3A	5.11%
Physical	Specific gravity	3.11
	Finess—specific surface	433 m^2/kg
	Initial setting time	198 min
	Final setting time	292 min
Mechanical	Compressive strength (1 day)	25.1 MPa
	Compressive strength (3 days)	38.6 MPa
	Compressive strength (7 days)	43.9 MPa
	Compressive strength (28 days)	51.9 MPa

Table 2
Characteristics of silica fume

Characteristics	Properties	
Chemical	SiO_2	95.1%
	Fe_2O_3	0.10%
	CaO	0.24%
	Al_2O_3	0.09%
	MgO	0.44%
	Na_2O	0.22%
	K_2O	0.93%
	Ignition loss	2.32%
Physical	Density (kg/dm^3)	2.22
	Specific surface	1420 m^2/kg

2.3. Concrete production

The following parameters were established for all the mix proportioning methods, so that the results obtained could be compared. These are:

- Workability evaluated by the slump test: 120 ± 20 mm;
- chemical admixture: added to the concrete during mixing, in minimum quantity, sufficient to reach the required workability;
- mineral admixture: 10% by mass of cement.

Table 3 shows the mix proportions used for the various mixes.

3. Test results

Six cylindrical test specimens, 10×20 cm, were moulded for each mix in accordance with the NBR 5738/94 [13] for determination of compressive strength

Table 3
Concrete batches (by mass of dry materials)

Batch	Cement	Fine aggregate	Coarse aggregate	Silica fume	Chemical admixture (% of binder)	w/cement ratio	Cementitious materials (kg/m^3)		
							Cement	Silica fume	Total
IPT/EPUSP method									
1	1.00	2.00	3.00	0.10	0.76	0.537	378	38	416
2	1.00	1.50	2.50	0.10	0.92	0.446	455	45	500
3	1.00	1.00	2.00	0.10	1.00	0.361	568	57	625
4	1.00	0.50	1.50	0.10	1.33	0.271	759	76	835
5	1.00	0.25	1.25	0.10	1.76	0.226	912	91	1003
Mehta/Aitcin method									
6	1.00	1.62	2.83	0.10	1.21	0.411	431	43	474
7	1.00	1.44	2.63	0.10	1.42	0.344	472	47	519
8	1.00	1.29	2.45	0.10	2.18	0.288	514	51	565
9	1.00	1.19	2.36	0.10	2.56	0.258	541	54	595
10	1.00	1.08	2.23	0.10	3.00	0.230	576	58	634
Toralles Carbonari method									
11	1.00	1.34	1.37	0.10	0.50	0.380	587	59	646
12	1.00	1.28	1.30	0.10	1.00	0.289	638	64	702
13	1.00	1.32	1.35	0.10	1.50	0.247	642	64	707
14	1.00	1.21	1.23	0.10	2.00	0.214	693	69	762
Aitcin method									
15	1.00	3.00	2.80	0.10	2.67	0.385	353	35	388
16	1.00	2.55	2.45	0.10	2.00	0.341	400	40	439
17	1.00	2.20	2.20	0.10	2.00	0.308	444	44	488
18	1.00	1.90	2.00	0.10	1.72	0.275	491	49	540
19	1.00	1.70	1.80	0.10	1.93	0.253	534	53	587

Table 4
Compressive strength test results at 3, 7 and 28 days

Batch	Compressive strength (MPa)		
	3 days	7 days	28 days
IPT/EPUSP method			
1	32.6	38.2	45.5
2	39.2	46.6	54.4
3	47.2	54.3	65.9
4	59.2	60.7	75.0
5	60.7	69.1	79.8
Mehta/Aitcin method			
6	45.3	51.9	65.7
7	55.6	62.2	76.0
8	58.5	64.1	80.0
9	69.0	71.5	88.9
10	71.3	75.4	86.0
Toralles Carbonari method			
11	43.8	50.4	61.2
12	57.4	62.4	68.4
13	64.9	66.7	83.1
14	62.4	73.4	84.7
Aitcin method			
15	41.1	48.1	58.9
16	48.8	58.1	72.1
17	55.0	61.2	76.0
18	69.4	75.6	82.2
19	69.4	77.5	88.4

at 3, 7 and 28 days by each repetition. The test specimens were cured according NBR 5738/94 (relative humidity $\geqslant 95\%$ at 23 ± 2 °C) and tested for compressive strength, in accordance with NBR 5739/94 [14]. According NBR 12655/96 the highest value of each batch was selected at 3, 7 and 28 days. The results presented in Table 4 give the average of those values [15].

4. Discussion of test results

It is well known that the majority of the conventional concrete strength results experimentally obtained obey Gauss normal distribution, principally the simple compressive strength results. However, this trend has to be proven, particularly in the case of the present research, which is about HSC, since there is still some doubt whether this trend is similar to that of conventional concrete. To guarantee the reliability of the results obtained in the tests, the verification of the normality of the distributions represented by each sample was checked. The Kolmogorov–Smirnov (KS) test was adopted to verify the normality of the distributions. This test consists on a comparison between observed accumulated frequencies (Dm) and the estimated frequencies by normal distribution ($D\alpha$). The hypothesis of normality cannot be rejected when $Dm \leqslant D\alpha$. The results of this analysis are given in Table 5, and it was found that the compressive strength test results of the HSC obey the Gauss normal distribution.

4.1. Cement consumption per m^3 of concrete

Table 6 presents the cement and cementitious materials consumption per cubic meter of concrete for the different mixes and methods studied. Strength ranges were established so it was possible to compare the different methods for the same strength. The values presented in Table 6 were obtained by regression analysis of strength results (Table 4) X w/c (Table 3); w/c X aggregates (Table 3) and aggregates X cement (Table 6). The equations and correlation coefficient are given in Table 7. All the correlations presented are linear model ($y = ax + b$). It is known that "strength X w/c" relation obeys Abram's law, but the correlation value shown to be as equal as linear adjustment, so by simplicity the linear adjustment was adopted. The equations and correlation coefficient are given in Table 7.

Concerning cement consumption per m^3 of concrete, it is clear that the Aitcin method is the one that represents the lowest consumption, followed by the Mehta/Aitcin method, which presents the second lowest

Table 5
Kolmogorov–Smirnov normality tests

Method (age)	Dm	$D\alpha$	$Dm \leqslant D\alpha$	Normal?
IPT (fc3)	0.11394	0.159	Yes	Yes
IPT (fc7)	0.08260	0.159	Yes	Yes
IPT (fc28)	0.12987	0.159	Yes	Yes
Mehta/Aitcin (fc3)	0.12087	0.192	Yes	Yes
Mehta/Aitcin (fc7)	0.15317	0.192	Yes	Yes
Mehta/Aitcin (fc28)	0.12195	0.192	Yes	Yes
Toralles Carbonari (fc3)	0.19248	0.213	Yes	Yes
Toralles Carbonari (fc7)	0.13359	0.1768	Yes	Yes
Toralles Carbonari (fc28)	0.13006	0.213	Yes	Yes
Aitcin (fc3)	0.11057	0.192	Yes	Yes
Aitcin (fc7)	0.16875	0.192	Yes	Yes
Aitcin (fc28)	0.09133	0.192	Yes	Yes

Obs: fc3, fc7 and fc28—compression strength distribution at 3, 7 and 28 days.
If $D_m \leqslant D_\alpha$, the distribution is normal.

Table 6
Cement and cementitious materials consumption per m^3 of concrete, in kg

fc28 (MPa)	IPT/EPUSP		Mehta/Aitcin		Toralles Carbonari		Aitcin	
	Cement	Cementitious materials	Cement	Cementitious materials	Cement	Cementitious materials	Cement	Cementitious materials
45	329	362	–	–	–	–	–	–
50	404	444	–	–	–	–	–	–
55	479	527	–	–	–	–	336	370
60	554	609	393	432	606	667	367	404
65	629	692	423	465	618	680	398	438
70	704	774	452	497	630	693	429	472
75	779	857	482	530	642	706	460	506
80	854	939	511	562	654	719	491	540
85	–	–	541	595	667	734	523	575
90	–	–	–	–	–	–	–	–

Obs: fc28 = compressive strength at 28 days.

Table 7
Correlation analysis

Method	Equation	Correlation coefficient (R)
IPT/EPUSP	$w/c = -0.0089\,fc28 + 0.9379$	1.00
	$m = 11.295\,w/c - 1.0589$	1.00
	$cem = -149.17m + 1076.8$	0.97
	$cost = -32.147m + 226.45$	0.96
Metha/Aitcin	$w/c = -0.0076\,fc28 + 0.9082$	0.96
	$m = 6.4323\,w/c + 1.8704$	1.00
	$cem = -121.17m + 972.09$	0.99
	$cost = -52.161m + 323.5$	0.98
Toralles Carbonari	$w/c = -0.006\,fc28 + 0.7268$	0.95
	$m = 1.2302\,w/c + 2.2525$	0.74
	$cem = -328.6m + 1494.4$	0.91
	$cost = -153.49 + 530.67$	0.84
Aitcin	$w/c = -0.0046\,fc28 + 0.6456$	0.97
	$m = 17.305\,w/c - 0.886$	1.00
	$cem = -78.156m + 797.67$	0.99
	$cost = -11.793m + 161.17$	0.94

Obs: fc28 = Compressive strength at 28 days, w/c = water/cement ratio, m = aggregates (sand + coarse aggregate, by mass), cem = cement consumption by cubic meter.

consumption of that material. The Toralles Carbonari method presents the highest consumption of cement per m^3 of concrete for the range between 60 and 65 MPa, being surpassed by the IPT/EPUSP method in the range from 70 to 80 MPa. As the methods cover different strength ranges, Fig. 1 has been prepared to show the cementitious material consumption for the range from 45 to 85 MPa.

4.2. Concrete cost per m^3

For the cost analysis of this research the following values were considered:

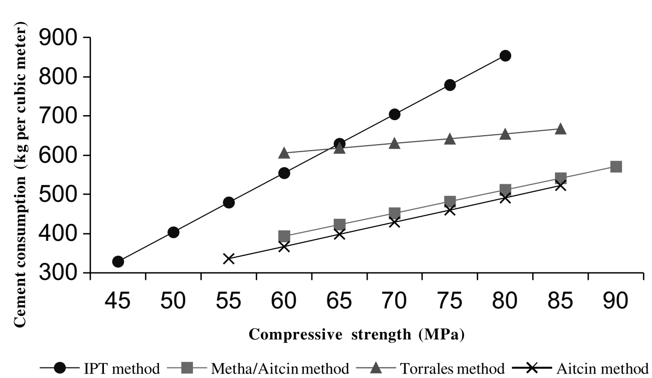

Fig. 1. Cement consumption for the compressive strength range from 45 to 85 MPa.

Table 8
Concrete cost per m^3, in U$

Compressive strength at 28 days (MPa)	IPT/EPUSP	Mehta/Aitcin	Toralles Carbonari	Aitcin
45	65	–	–	–
50	82	–	–	–
55	98	–	–	91
60	114	74	116	96
65	130	87	121	101
70	146	100	127	106
75	162	112	133	110
80	178	125	138	115
85	–	138	144	120
90	–	151	–	–

- Cement: U$ 0.12/kg;
- Silica fume: U$ 0.25/kg;
- Fine aggregate: U$ 7.22/m^3;
- Coarse aggregate: U$ 10.00/m^3;
- Superplasticizer: U$ 3.33/kg.

Table 8 presents the cost comparison per cubic meter of concrete for the different strength ranges and for the different mix proportioning methods. It can be seen that they cover a wide range of costs.

Fig. 2 illustrates the cost per cubic meter of concrete, for the different strength ranges and for the four methods studied.

Although the Aitcin method has shown the lower consumptions of cement per cubic meter of concrete, Fig. 2 shows that it does not always represent the highest savings. In the range from 65 to 75 MPa, the Mehta/Aitcin method appears to be slightly more cost saving one. However, from 80 MPa onwards, the Mehta/Aitcin and Aitcin methods appear to give the lowest cost. For concretes of the order of 55 MPa, the IPT method appears to be as good as any other method. For the range from 45 to 50 MPa, the IPT method appears to be an efficient method for conventional concrete. However, from 60 MPa onwards, it practically classifies as the least cost saving one for all levels of compressive strength studied. The Toralles Carbonari method, although not representing the highest costs does present rather high costs if compared to the Mehta/Aitcin and Aitcin methods. From Fig. 2, it may be noted that there are some points where the curves cross each other, indicating that there is no method that will always be the most cost saving one. The cost has to be analyzed for each compressive strength range. At the moment the choice of the method, depending on the strength wished to be reached, should fall on one or another method.

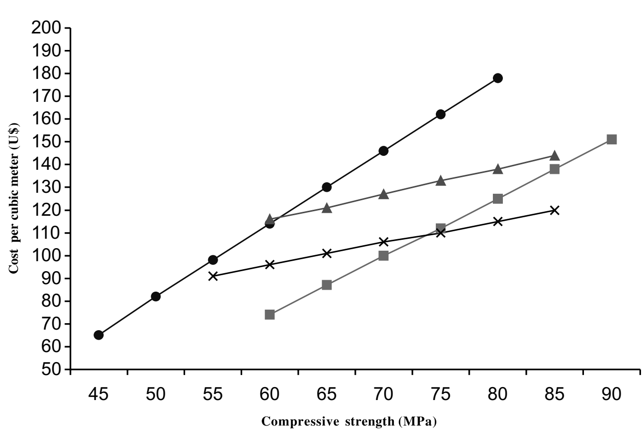

Fig. 2. Cost of m^3 concrete for the compressive strength range from 45 to 85 MPa.

4.3. Proportioning diagram

From the proportioning diagram it is possible to estimate the cement (binder) consumption, the (cement) binder:aggregate ratio (“*m*”) and the w/b ratio for any compressive strength within the studied range and with the materials used. Fig. 3 shows the proportioning diagram for the IPT, Mehta/Aitcin and Aitcin methods. The Toralles Carbonari method, for following different criteria, does not allow building a proportioning diagram.

5. Conclusions

The use of HSC is increasing, due to the innumerable advantages it brings, when compared to the use of conventional concrete or construction materials. There are different proportioning methods for HSC that differ from one another in terms of characteristics of materials, and based on departing different principles.

The present research investigated four mix proportioning methods for concrete, three being specific for HSC and one for conventional concrete.

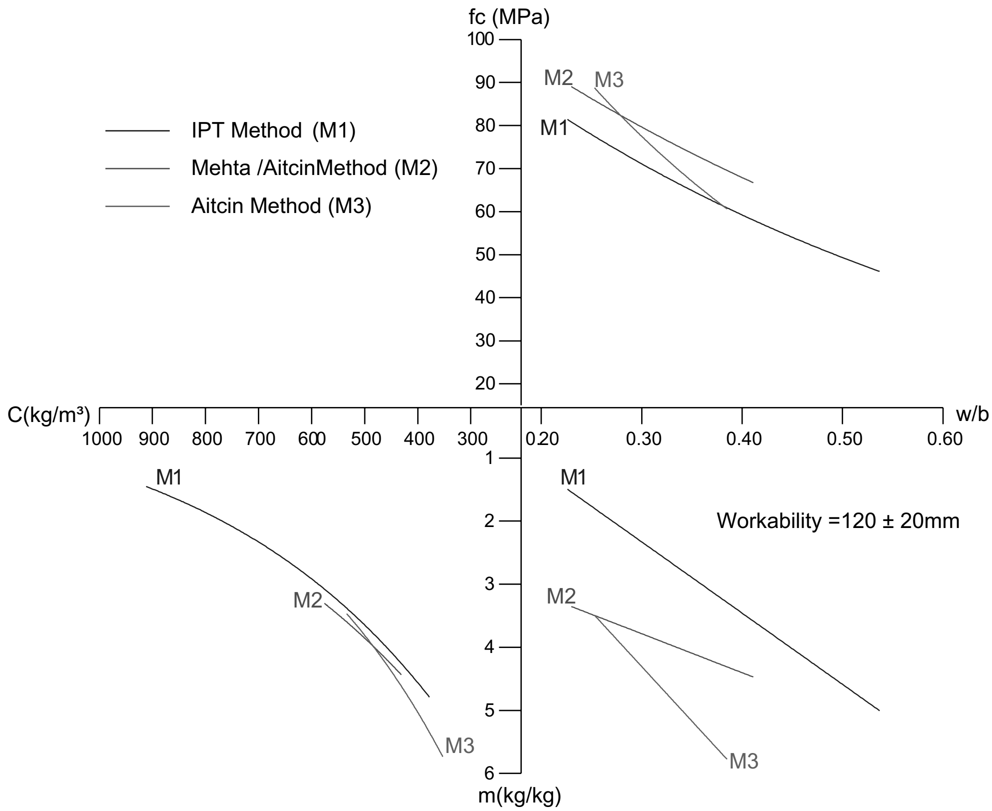

Fig. 3. Proportioning diagram.

From the results achieved for the compressive strength tests it is possible to draw the following conclusions:

1. There is a significant difference between producing HSC as per HSC specific proportioning methods and proportioning methods for conventional concrete.
2. The material consumption per cubic meter of concrete, particularly of cement, varies considerably from one method to another, and for HSC specific methods this consumption is highly reduced.
3. As to the compressive strength all proportioning mixing methods enabled concrete of the order of 80–90 MPa to be obtained.
4. It was possible to produce concrete with a compressive strength of an order of 85 MPa with cement consumption from 500 to 550 kg/m^3. It is known that there must be a limit to the cement consumption in order to avoid cracking due to thermal changes and drying;
5. Concerning the cost per cubic meter of HSC, it is shown that the concrete having the highest consumption of cement per cu m^3 of concrete is not, necessarily, always the most expensive one.

References

[1] Metha PK, Monteiro P. Concreto: estrutura, propriedades e materiais. São Paulo: PINI; 1994.
[2] Nawy EG. Fundamentals of high strength high performance concrete. London: Longman Group Ltd; 1996.
[3] Mehta PK. Advancements in concrete technology. Concr Int 1999;(June):69–76.
[4] Mindess S. High performance concretes and applications. London: Edward Arnold; 1994.
[5] Mehta PK, Aitcin PC. Microstructural basis of selection of materials and mix proportions for high strength concrete. In: HSC International Symposium on Utilization on High Strength Concrete, vol. 2. Berkeley, CA, 1990.
[6] Domone P, Soutsos M. An approach to the proportioning of high-strength concrete mixes. Concr Int 1994;16(10):26–31.
[7] Toralles Carbonari BM, Carbonari G. Concreto de alto desempenho: do laboratório à obra. Florianó polis: ENTAC—Encontro Nacional da Tecnologia do Ambiente Construído, Florianópolis, 1998, 76p.
[8] Alves MF. Estudo comparativo de métodos de dosagem para concreto de alta resistência. Porto Alegre, 2000. Thesis (MsC)—Universidade Federal do Rio Grande do Sul - Porto Alegre. 149p.
[9] Aitcin PC. High-performance concrete. London: E & FN Spon; 1998. 591p.
[10] Helene P, Terzian P. Manual de Dosagem e Controle do Concreto. São Paulo: PINI; 1992. 349p.

[11] Mehta PK, Aitcin PC. Principles underlying production for high strength performance concrete. Cement, Concr Aggr 1990;12(2): 70–8.
[12] Toralles Carbonari BM. Estudio paramétrico de variables y componentes relativos a la dosificación y producción de hormigones de altas prestaciones. Barcelona, 1996. Thesis (PhD) Universitat Politècnica de Catalunya, Barcelona. 174p.
[13] Associação Brasileira de Normas Técnicas. Moldagem e cura de corpos de prova de concreto cilíndricos ou prismáticos: NBR 5738. Rio de Janeiro, 1994.
[14] Associação Brasileira de Normas Técnicas. Ensaio de compressão de corpos de prova cilíndricos de concreto: NBR 5739. Rio de janeiro, 1994.
[15] Associação Brasileira de Normas Técnicas. Preparo, controle e recebimento de concreto: NBR 12655. Rio de Janeiro, 1996.