SP 144-25

Designing Concrete Mixtures for Desired Mechanical Properties and Durability

by P.J.M. Monteiro and P.R.L. Helene

Synopsis: There are many methods for determining the mixture proportions of concrete when compressive strength is the design criterion. However there is not much information when other criteria, such as fracture energy , elastic modulus, or durability aspects are specified. For these cases a new mix design nomogram developed from well-established concrete relationships is reported in this paper. The application of this method is demonstrated by showing the influence of cement content, water-cement ratio and aggregate-cement ratio on the compressive strength, modulus of elasticity, fracture energy, depth of carbonation, and permeability. The mixture design nomogram, besides being a tool for the practitioner, can also help the researcher select the most appropriate parameters for experimental studies.

Keywords: Carbonation; cement content; compressive strength; durability; fracture properties; mechanical properties; mix proportioning; modulus of elasticity; permeability; water-cement ratio.

Paulo J.M. Monteiro, member of ACI, is an associate professor of Civil Engineering at the University of California at Berkeley, where he received his Ph.D. degree. His research interests include mathematical modeling and microstructure of concrete and testing methods. He held the Roy W. Carlson Distinguished Professorship at U.C. Berkeley during 1987-88. Prof. Monteiro received the Presidential Young Investigator award from NSF in 1989.

Paulo R. L. Helene, member of ACI, is an associate professor of Civil Engineering at the University of São Paulo, Brazil. His interests include mixture design of concrete, corrosion and repair of reinforced concrete.

1. INTRODUCTION

This work briefly reviews the evolution of various methods of concrete mixture proportioning and introduces a nomogram for quick prediction of the fresh and hardened concrete properties. The nomogram is based on three basic relationships developed for fresh and hardened concrete. The first is Abrams'[1] law for the compressive strength as a function of the water-cement ratio. The second relationship is based on the work of Lyse[2] who showed that when using the same materials it is possible to obtain concrete mixtures with the same consistency by keeping constant the ratio between the volume of water to volume of compacted fresh concrete. Using this rule it is possible to obtain fresh concretes with the same consistency but very different mix proportions and consequently different mechanical properties. The third relationship was formulated by Molinari[3] who correlated the cement content with the aggregate-cement ratio. Once the trial mixes are performed, these three relationships are arranged in a graphical form which permits the determination of mixture proportions for a specified property.

The application of this method is demonstrated by experimental results showing the influence of cement content, water-cement ratio and aggregate-cement ratio on properties of concrete such as compressive strength, modulus of elasticity, fracture energy, characteristic length, depth of carbonation, and permeability.

It is pointed out that when studying the effect of the mixture parameters on properties of concrete certain constraints should be used. For instance when varying the water-cement ratio, the workability of fresh concrete should be kept constant and vice versa. Under these conditions the mix parameters may have different effects on the concrete properties; for example a decrease in cement content or an increase in aggregate content leads to an increase in the fracture energy for a constant water-cement ratio, and leads to a decrease in the fracture energy for a constant workability.

2. EVOLUTION OF METHODS FOR CONCRETE MIX PROPORTIONING

Vicat[4] in 1818 showed the importance of the mixing water content and sand granulometry to the strength of mortar. His experimental results indicated that a given cement-to-sand ratio gave the maximum mortar strength. He also showed that excessive water reduced the strength of the mortar and he warned against the excessively fluid mortars that were used in his time. Rondelet[5] in 1830 suggested that the nature of the sand is not fundamental for the mortar strength because only its fineness significantly affects the final product. Préaudeau[6], in 1881, proposed a mix proportioning method for mortars and concretes. He suggested that the volume of paste should be 5% higher than the volume of voids existing in the fine aggregates. Also the volume of mortar should be 10% higher than the volume of voids existing in the coarse aggregate. These ideas were expanded by Lecleroc du Sablon[7] in 1927 when he proposed the use of discontinuous gradation.

In 1888, Alexandere[6] studied in greater details the effect of mixing water on the strength of mortar. Feret[8] developed the first rational method of proportioning the materials. In 1892, Feret observed experimentally that the compressive strength of mortars was a function of the absolute volume of water and volume of voids. In 1896, he proposed the following expression[9]:

$$f_{cj} = k_1 \left(\frac{C_{abs}}{1 - M} \right)^2$$

where

f_{cj} mortar compressive strength at j days

k_1 constant

C_{abs} absolute volume of cement per unit volume of mortar

M absolute volume of fine aggregate per unit volume of mortar

A significant contribution was made by Fuller in 1901, when he established the effect of the granulometry curves on the compressive strength. Abrams[1] had tested over 50,000 concrete specimens to prove that for plastic concretes, the strength is inversely proportional to the water-cement ratio. Abrams also introduced the fineness modulus to characterize the granulometric distribution of aggregates. Subsequently, he also developed the slump test to measure the consistency of concrete. Talbot and Richart[10] showed in 1923 the limitations of the Abrams' law for non-plastic concretes , and Lyse[2] demonstrated that the water content is the most important parameter for the consistency of fresh concrete. Lyse also suggested to use the water-cement ratio by mass and not by volume as proposed by Abrams.

Bolomey[11] studied the workability as affected by the Fuller granulometric curves, and Caquyot[12] analyzed the wall effect. Faury[13] proposed a mix proportioning based on the granulometric curve that included the workability and the wall effect. ACI Committee 613 first published its mix proportioning recommendations in 1944. In 1954 the text was revised to include, among other modifications, the use of entrained air. In 1970, mixture proportioning became the responsibility of ACI Committee 211.

Thomas[14] and Mimsworth[15] showed the importance of using statistical methods to characterize the concrete production. Murdock[16] studied the workability of concrete as a function of the granulometry of aggregates and the shape and nature of aggregate particles. Popovics[17] proposed a simplified model to predict the amount of water necessary to obtain a given consistency.

The studies of rheology of fresh concrete started with the work of Rober L'Hermite and Tournon[18] at the "Centre d'Etudes et des Recerches de l'Institute des Liants Hydrauliques ". Their work was expanded by Tattersall[19] in England and by Bombled[20] in France. Tattersall proposed that only two parameters are necessary to characterize the rheology of fresh concrete.

Powers[21] proposed a very comprehensive mix proportioning method. Table 1 summarizes the history of evolution of mix proportioning methods. Nowadays, the research trend is to computerize the mix proportioning methods and to develop methods for proportioning very high strength concrete mixtures[22-24].

3. MIX DESIGN NOMOGRAM

As discussed below, the proposed mix design nomogram shown in Fig. 1 combines three relationships , which were developed for the properties of fresh and hardened concrete.

(i) Abrams' law correlates the concrete compressive strength with the water-cement ratio (by weight) for a given level of cement hydration. Since the water-cement ratio is the most important variable in concrete, this relationship can also be extended to other properties such as modulus of elasticity, permeability and fracture energy. For a given workability, the equation which best fits this law is:

$$f_c = \frac{k_1}{k_2^{w/c}}$$ where;

f_c = compressive strength (MPa),
k_1, k_2 = constants which depend on the materials used,
w/c = water-cement ratio, (kg / kg).

(ii) Lyse's law correlates the water/cement ratio with the (fine + coarse aggregates)/cement ratio (by mass):

$$m = k_3 \bullet w / c + k_4$$ where;

m = aggregates - cement ratio (kg / kg),
k_3, k_4 = constants which depend on the materials used on the a given workability
w/c = water-cement ratio, (kg / kg).

(iii) Molinari's law which correlates the cement content, C, and the aggregates-cement ratio, m. The equation that best fits this behavior is[3,25]:

$$C = \frac{1000}{k_5 \bullet m + k_6} \quad \text{where;}$$

C = cement content (kg / m^3),
k_5, k_6 = constants which depend on the materials used,
m = aggregates -cement ratio (kg / kg).

The nomogram shown in Fig. 1 indicates that changing one variable causes a change in all other parameters of fresh and hardened concrete. The water-cement ratio is the most important variable in the concrete mix proportioning and it can significantly change the properties of hardened concrete. To avoid its influence when studying the effect of other variables, such as cement content and aggregate-to-cement ratio, the water-cement ratio should be kept constant. When the water-cement ratio is kept constant, any change in the concrete mix proportioning causes a change in the consistency of the fresh concrete, modifying the slump as shown in Fig. 1.

To analyze the influence of water-cement ratio on properties of concrete, it is necessary to fix other variables such as consistency of fresh concrete, cement content, or aggregate content. Producing concretes with the same cement content or the same aggregate content and different water-cement ratio means changing significantly the consistency of these concretes. If this option is taken, the experimental research will have many limitations[26]. It is therefore recommended that the water-cement ratio should be modified using the criterion of maintaining the same consistency of fresh concrete. Using this condition, the influence of water-cement ratio on the properties of hardened concrete can be studied without the influence of other variables.

4. COMPRESSIVE STRENGTH

For most practical applications the compressive strength has been selected as the performance criteria. The nomogram presented in Figure 1 allows the quick determination of the effect of mixing parameters and properties of fresh concrete on the compressive strength. The nomogram also permits the engineer to perform quick and reliable changes in the mixture design. The following sections will show how the nomogram can be modified to incorporate different performance criteria. The nomograms and figures presented in sections 4-6 are based on experimental results of concrete specimens prepared according to the mix proportions shown in Table 2. Figure 2 shows a typical nomogram for a constant consistency of fresh concrete. Figures 3 and 4 indicate that for a constant water-cement ratio the compressive strength is basically independent of the cement content and of the aggregate to cement ratio, as expected from the Abrams' law and Power's model. For a constant consistency the compressive strength increases with the cement content (Fig. 5) and decreases with the aggregate-cement ratio (Fig. 6). This is because in order to keep the consistency constant , an increase in cement content requires a decrease in the water-cement ratio while an increase of aggregate content requires an increase in the water-cement ratio.

The use of a water-reducing admixture allows the reduction of cement content for the same consistency and water-cement ratio. The nomogram is shown in Figure 7.

5. MODULUS OF ELASTICITY

For normal strength concrete, the aggregate is normally stronger than both the matrix and the transition zone, therefore the strength of these two weaker phases, which is controlled by the water-cement ratio and degree of hydration, is the limiting parameter to the strength of concrete, as indicated in Fig. 1. The elastic modulus however, is greatly influenced by other mix parameters, such as the volume of aggregate or cement content. This is reflected in Fig. 8 where instead of having only one curve in the first quadrant (as in the case of Fig. 1), a series of curves associated with the volume fraction of component phases are necessary.

Special mix design nomograms can be obtained when the modulus of elasticity is selected as performance criteria. Figure 9 shows a typical nomogram for a constant consistency of fresh concrete. The effect of the cement and aggregate content on the modulus of elasticity of concrete should be studied under two conditions: (a) constant consistency and (b) constant water-cement ratio. For a constant consistency, the modulus of elasticity increases with increasing cement content, as indicated in Figs. 10. To keep the consistency constant , an increase in cement content requires a decrease in the water-cement ratio and therefore results in a stronger and stiffer matrix. Figure 11 shows the influence of the cement content on the modulus of elasticity of concrete for a constant water-cement ratio. It should be noted that under this condition, an increase in cement content results in a reduction in the modulus of elasticity. This dependency is significantly different from the condition of constant consistency (Fig 10). The result is expected because an increase in cement content leads to a reduction in the aggregate content; as the aggregate has a higher modulus of elasticity than the cement paste, reducing the aggregate content would cause a decrease in the elastic modulus of concrete.

For a constant consistency, an increase in the aggregate-cement ratio causes an increase in the water-cement ratio leading to a reduction in the modulus of elasticity. Normally it is expected that the modulus of elasticity will increase with increasing percentage of aggregate. However as indicated in Fig. 12, this does not happen because the increase of elastic modulus is over-shadowed by a weaker and less stiff matrix. When the consistency is not kept constant whereas the water-cement ratio is constant, the matrix has constant mechanical properties, so the modulus of elasticity increases with higher content of aggregate as shown in Fig. 13.

6. FRACTURE ENERGY

Special mix design nomograms (Fig. 8) can be obtained when the fracture energy (G_f) is selected as a performance criterion. Figure 14 shows a typical nomogram for a constant consistency of fresh concrete. The fracture energy was obtained according to the RILEM 50 - FMC COMMITTEE. As discussed in Section 5, the effect of cement and aggregate contents on a property of concrete should be studied under two conditions: (a) constant consistency and (b) constant water-cement ratio. For a constant consistency, the fracture energy increases with increasing cement content (Fig 15) since an increase in cement content requires a decrease in the water-cement ratio and therefore producing a stronger and stiffer matrix. Figure 16 shows the influence of the cement content on the fracture energy of concrete for a constant water-cement ratio . Again under this condition the dependency of the fracture energy on the cement content is significantly different from the condition of constant consistency. The fracture energy decreases with the cement content for a constant water-cement ratio. The reason for such a decrease is similar to the elastic modulus dependency, that is, there is less aggregate with increasing cement content.

The ratio between the slopes of stress-strain and stress-elongation curves of concrete is in length units , and it is called the **characteristic length** (l_{ch}) of the material:

$$l_{ch} = \frac{E\,G_f}{f_t^2}$$

where f_t is the tensile strength of concrete. The characteristic length is often considered to be a material property, and it gives a measure of the brittleness of the material. Cement paste has a characteristic length in the range 5-15 mm, mortar in the range 100-200 mm, and concrete in the range 130-400 mm. Compared to normal-strength concrete, high-strength concretes and light-weight aggregate concrete have lower characteristic lengths. The characteristic length decreases with increasing cement content both for constant consistency and constant water-cement ratio, as indicated in Figs. 17 and 18. With constant consistency, this decrease is associated with lower water-cement ratio for higher cement content. Petersson[27] also verified that the characteristic length decreases for lower water-cement ratios. For constant water-cement ratio, the decrease of the characteristic length with the cement content is due to a reduction in the amount of aggregate and therefore a corresponding reduction in the energy absorption capacity.

For a constant consistency, an increase in aggregate-cement ratio causes an increase in the water-cement ratio, leading to a reduction in fracture energy. When the consistency is not kept constant but the water-cement ratio is kept constant, the matrix has the mechanical properties approximately constant, so that the fracture energy increases with higher content of aggregate. The characteristic length increases with the aggregate-cement ratio both for constant consistency and constant water-cement ratio. For constant consistency, the increase is associated with a higher water-cement ratio, for the condition of constant water-cement ratio, the increase of the characteristic length with higher aggregate concentration is due to the significant influence the aggregate has on the elastic modulus and fracture energy of concrete. Typically the rate of increase of the characteristic length for constant water-cement ratio is higher than that with constant consistency. One explanation is that while the tensile strength remains about the same for constant water-cement ratio, both the elastic modulus and fracture energy show significant increases, therefore increasing the characteristic length.

7. DURABILITY

In the previous sections, it has been shown that the effect of cement and aggregate contents on the mechanical properties of concrete should be studied under (a) constant consistency and (b) constant water-cement ratio. The same approach should be taken when analyzing the effect of mix proportioning parameters on durability of concrete. Table 3 summarizes the effect of cement content both for constant consistency and constant water-cement ratio. For a constant consistency, increasing the cement content leads to a decrease in the water-cement ratio. This causes a significant reduction in the porosity of the matrix, which not only increases the strength, but also decreases the coefficient of permeability, the carbonation, and the depth and amount of capillary absorption. For a constant water-cement ratio, the porosity of the matrix remains approximately the same, therefore the strength and the coefficient of permeability are not affected by increasing the amount of cement. The capillary pores, under this condition, have the same diameter and shape, therefore the depth of carbonation and of capillary absorption are independent of the cement content. However, the amount of paste is greater with increasing amount of cement, therefore the amount of capillary pores per unit volume increase, leading to a greater amount of capillary absorption. It should be pointed out that the same type of nomograms can be established for the durability parameters as a design criteria. In the first quadrant of Figure 1, a specified durability parameter is selected and the same procedure is used to determine the concrete mix proportioning follows.

8. CONCLUSIONS

A useful mixture design nomogram can be obtained by combining three relationships dealing with the properties of fresh and hardened concrete. With such nomograms, it is possible to determine mixture proportions which comply with the predefined performance criteria other than compressive strength. A comparison of properties from concrete mixtures with different mixture proportions is also possible with the help of these nomograms.

The effects of the mixture parameters on properties of concrete can be easily determined if the analysis is performed under two conditions: constant consistency and constant water-cement ratio. In this paper special attention is given to the design of mixtures with properties such as elastic modulus, fracture energy and durability of concrete. It is expected that in the near future the designers will specify mixture proportion for concrete for specific criteria that best fit the project in hand.

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TABLE 1 — SUMMARY OF THE CHRONOLOGICAL EVOLUTION OF THE METHODS OF MIX PROPORTIONING OF CONCRETE

Period	Researcher		Contribution
Up to 1891	Vicat	1828	• granulometry of sand, inconvenience of excess of water
Beginning of the technology of cements, mortar and concretes	Rondelet	1830	• importance of sand fineness
	Préadeau	1881	• discontinuous granulometry
	Le Châtelier	1887	• main compound composition of portland cement
1892 to 1951	Ferét	1892	• correlation between strength and compactness
	Fuller	1901	• reference curve for the ideal granulometry
	Abrams	1918	• correlation between strength and water-to-cement ratio, fineness modulus, slump test
	Talbot and Richard	1923	• b/bo method to determine the coarse aggregate consumption
Classical Methods of Mix Proportioning	Bolomey	1925	• improves Fuller's curve
	Du Sablon	1927	• discontinuous granulometry
	Inge Lyse	1931	• importance of water content on the consistency of concrete
	Lobo Carneiro	1937	• improvement of Bolomey's curve
	Blanks	1944	• ACI committee
	Vallete	1949	• mix proportioning based on discontinuous granulometry
1936-1978	Oliveira	1939	• statistical methods applied to the strength of concrete
	Walker	1944	• statistical methods applied to the mix proportioning (1%)
Statistical Methods	Morgan	1944	• mix proportioning based on the minimum strength (1%)
	Lobo Carneiro	1944	• mix proportioning based on the minimum strength (2.5%)
	CEB, CIB,FIP, Rilem	1944	• standard deviation to characterize the concrete production
1950-1978	L'Hermite	1950	• rheological models
	Tattersall	1957	• improves the rheological studies
Comprehensive Models	Bombled	1968	• relationship between rheology and hardened concrete
	Powers	1968	• comprehensive mix proportioning
	Tattersall	1978	• comprehensive study of concrete rheology
1958-1993	Kurt Walz	1958	• reference curves
	Murdock	1960	• simplified formulas for workability of concrete
Improvement of the Methods	Popovics	1968	• simplified criteria to adjust the mix proportions
	Larrard	1985	• comprehensive study of mix proportioning for high strength concrete
	Mehta and Aitcin	1990	• simplified methods for proportioning high strength concrete

TABLE 2 — MIX PROPORTIONS FOR FRESH CONCRETE

MIX PROPORTIONS	SI Units	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Cement	kg / m^3	478	398	329	282	306	484
Fine Aggregate	kg / m^3	765	866	929	976	1023	721
Coarse Aggregate	kg / m^3	902	920	914	911	961	875
Water	kg / m^3	196	199	198	198	153	242
Entrapped air	% vol.	0.09	0.76	0.63	0.51	0.57	0.65
m[(fine+coarse agg.)/cem.]	kg / kg	3.49	4.49	5.59	6.69	6.50	3.30
w/c [water/cem. ratio]	kg / kg	0.41	0.50	0.60	0.70	0.50	0.50
Slump	cm	5±1	5±1	5±1	5±1	<1	20±3
Specific Weight	kg / m^3	2339	2365	2355	2355	2429	2307

TABLE 3 — EFFECT OF INCREASING CEMENT CONTENT ON CONCRETE PROPERTIES

Property	constant slump and variable w/c	constant w/c and variable slump
strength	increases	same
coefficient of permeability	decreases	same
carbonation depth	decreases	same
amount of carbonation	decreases	increases
depth of capillary absorption	decreases	same
amount of capillary absorption	decreases	increases
amount of water absorption	decreases	increases

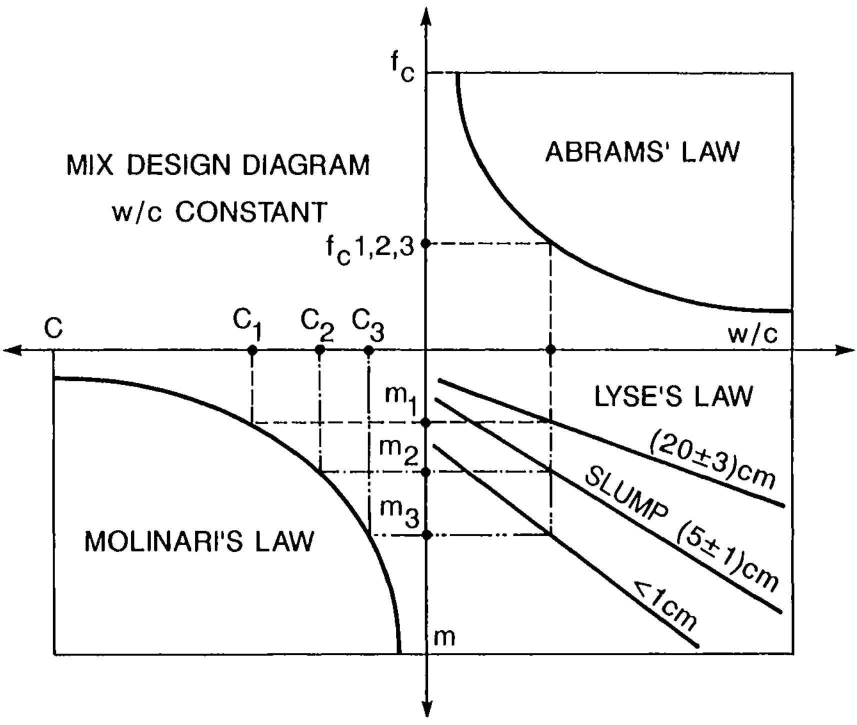

Fig. 1—Mix design nomogram for a given water-cement ratio. Compressive strength as the design criterion

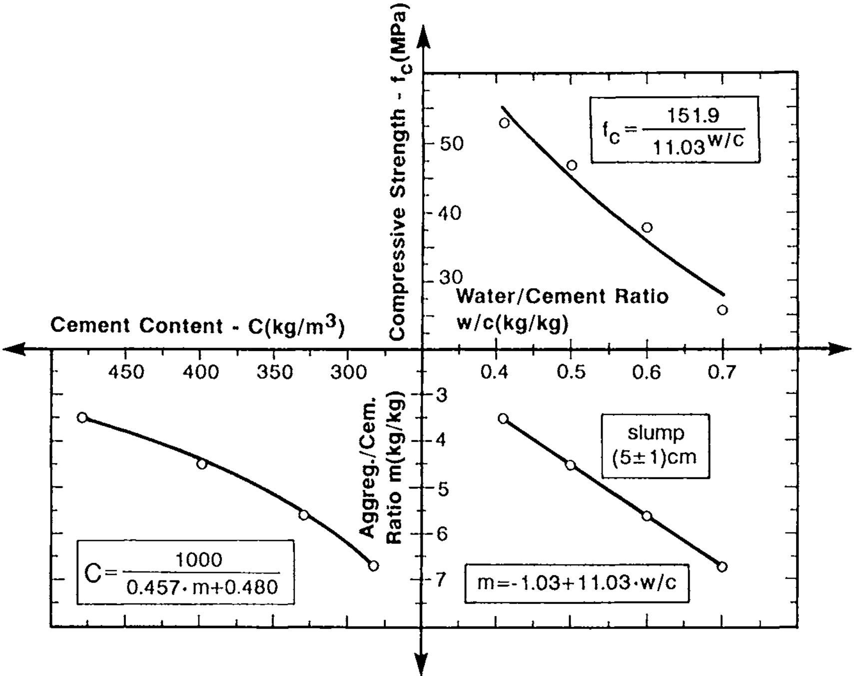

Fig. 2—Mix design nomogram for a given consistency of fresh concrete. Compressive strength as the design criterion

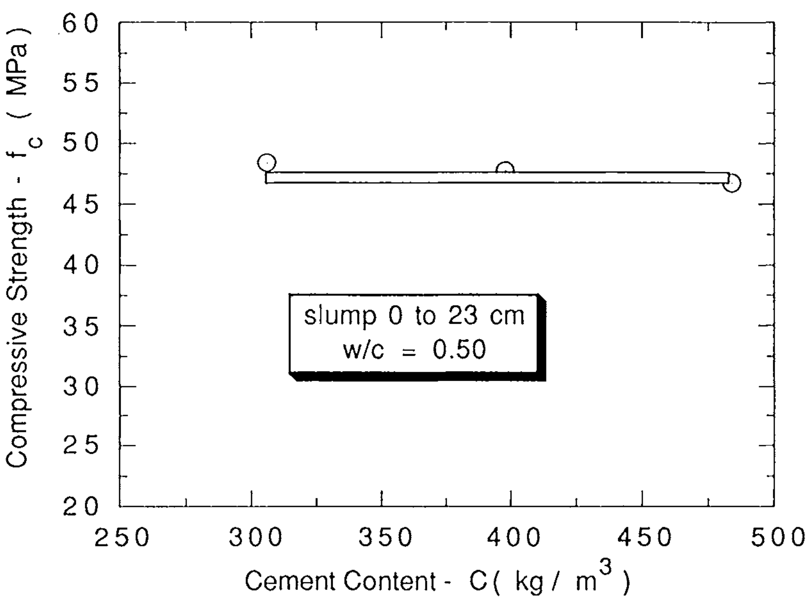

Fig. 3—Effect of cement content on the compressive strength for a constant water-cement ratio

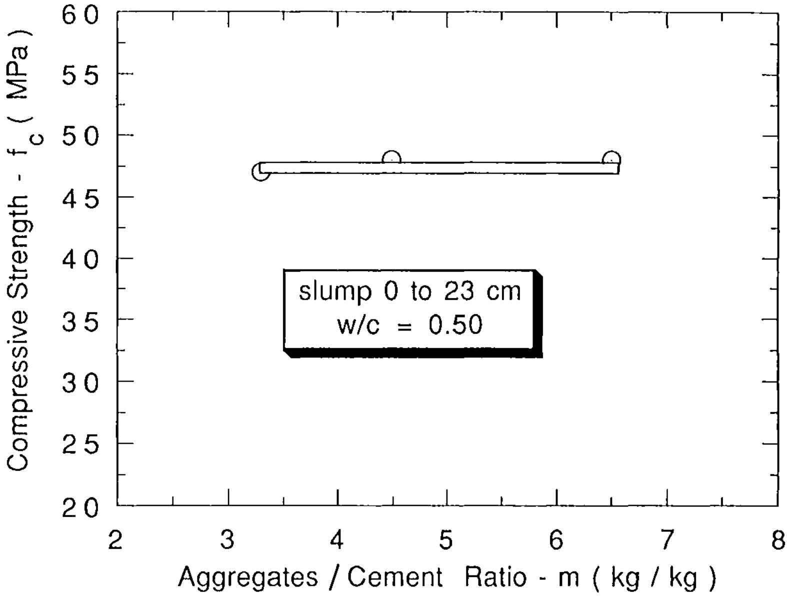

Fig. 4—Effect of aggregate-cement ratio on the compressive strength for a constant water-cement ratio

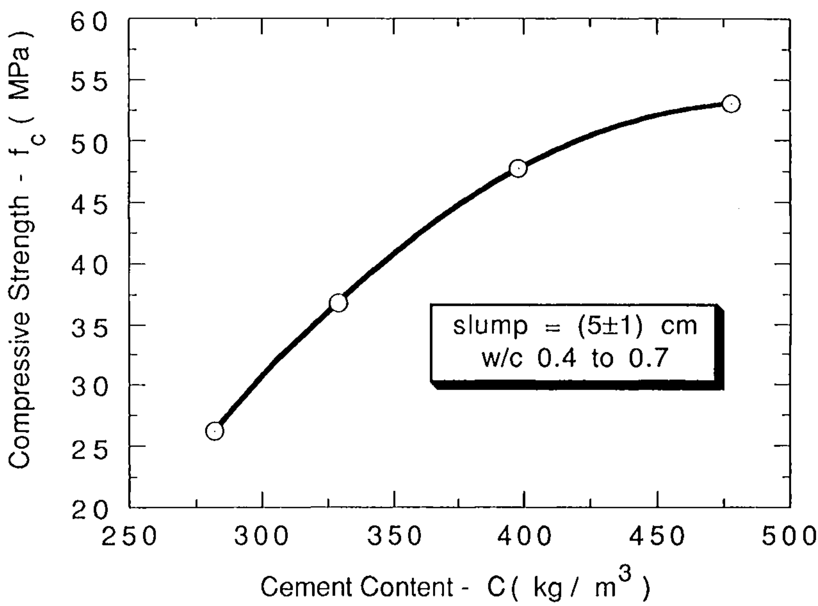

Fig. 5—Effect of cement content on the compressive strength for a constant consistency

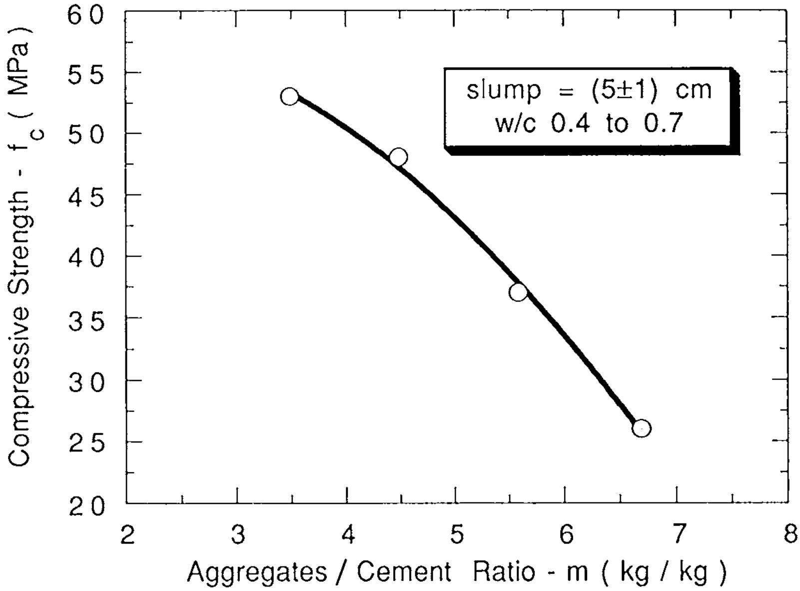

Fig. 6—Effect of aggregate-cement ratio on the compressive strength for a constant consistency

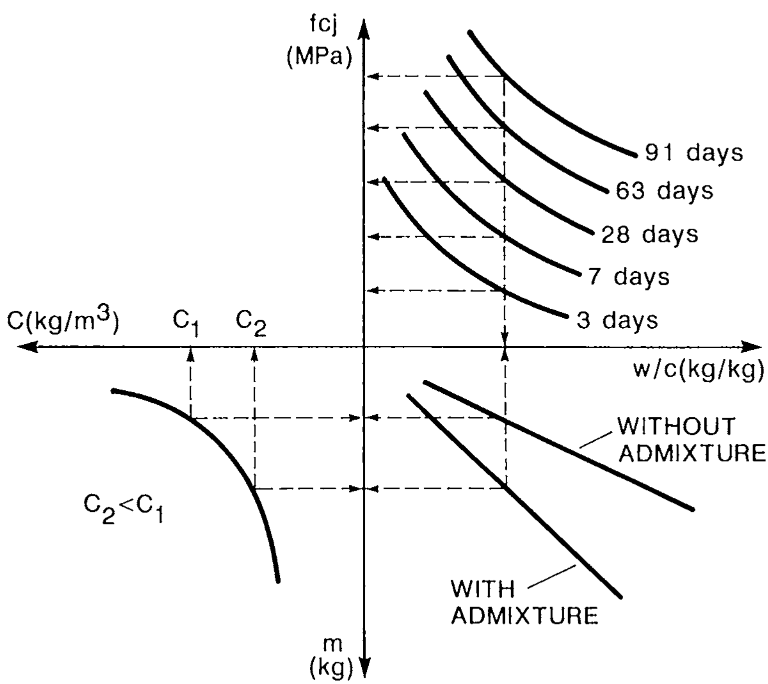

Fig. 7—Effect of water-reducer on the mix design nomogram

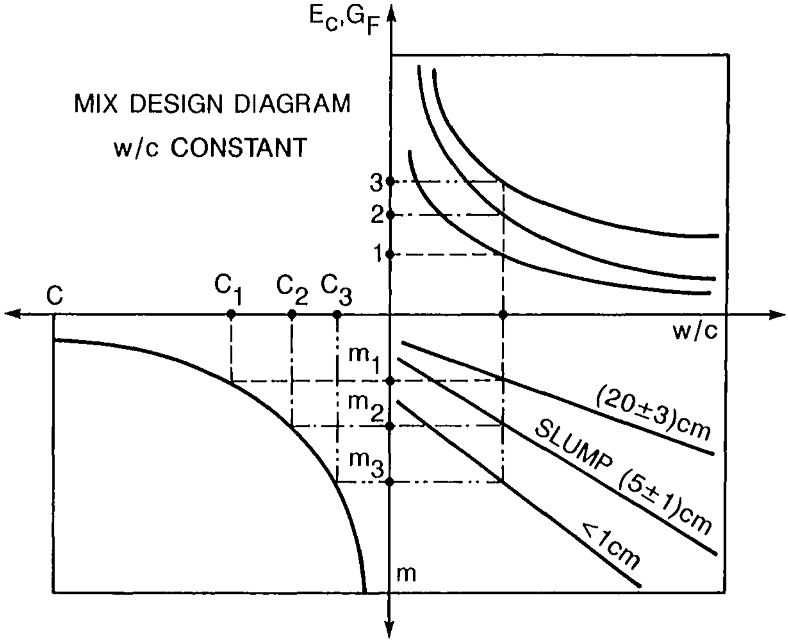

Fig. 8—Mix design nomogram for a given water-cement ratio. Modulus of elasticity or fracture energy as the design criterion

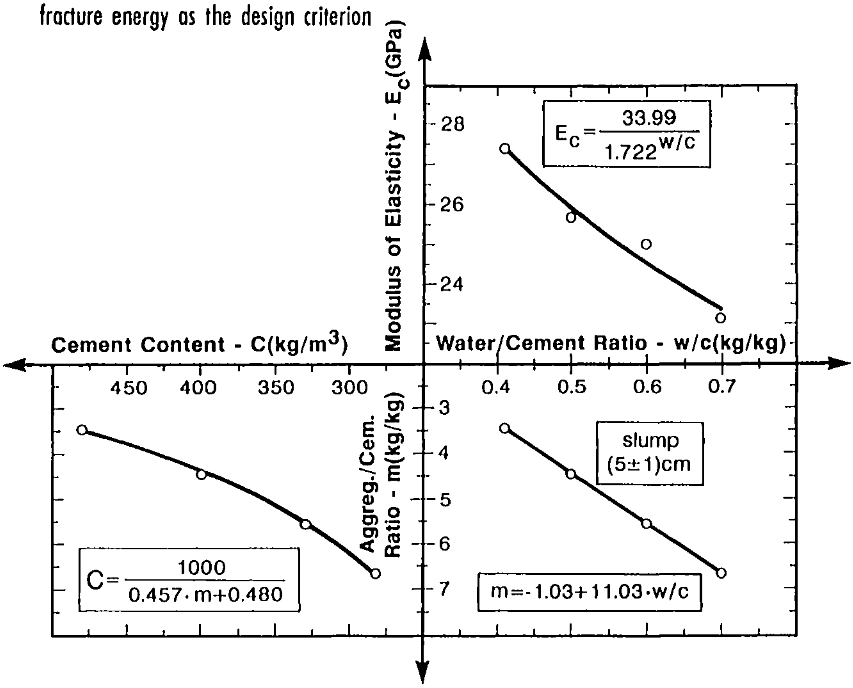

Fig. 9—Mix design nomogram for a given consistency of fresh concrete. Modulus of elasticity as the design criterion

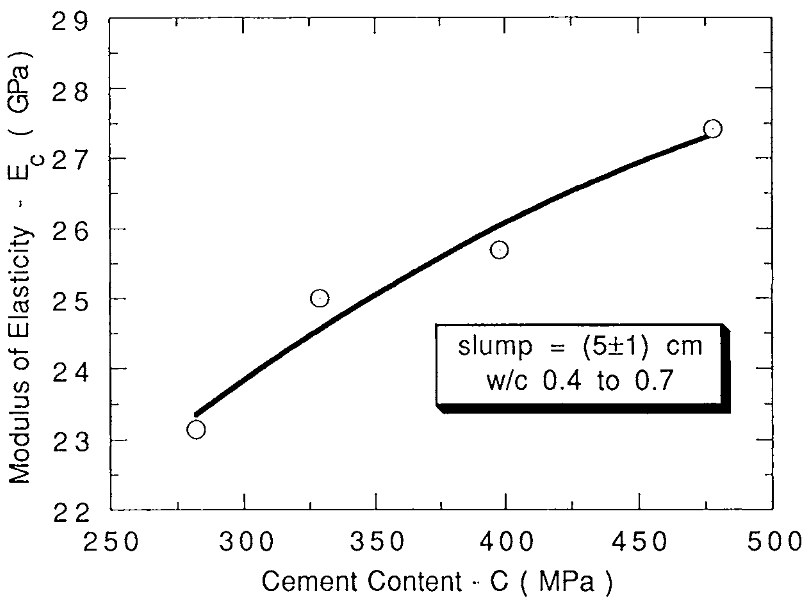

Fig. 10—Effect of cement content on the modulus of elasticity for a constant consistency

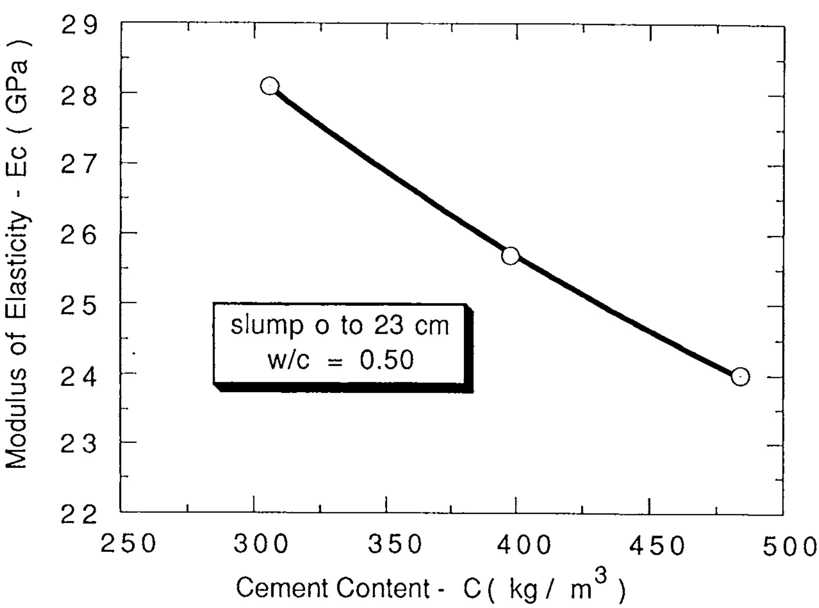

Fig. 11—Effect of cement content on the modulus of elasticity for a constant water-cement ratio

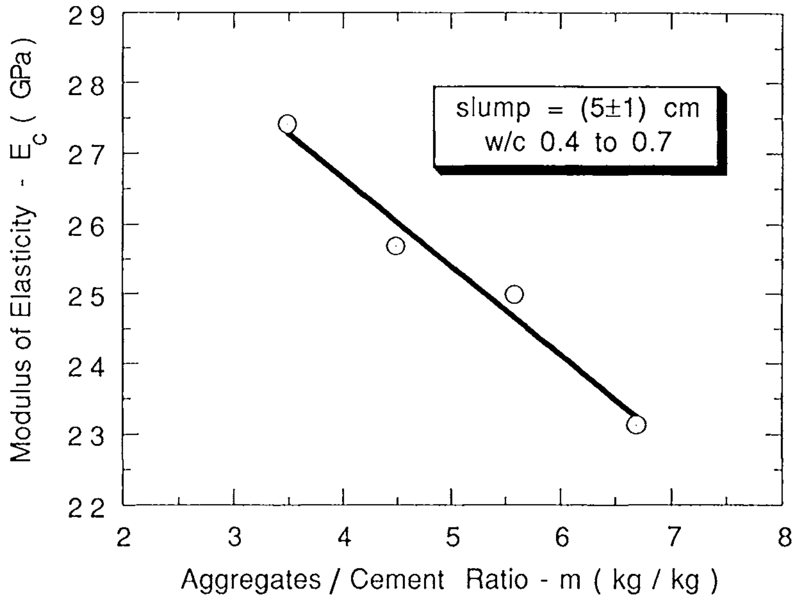

Fig. 12—Effect of aggregate-cement ratio on the modulus of elasticity for a constant consistency

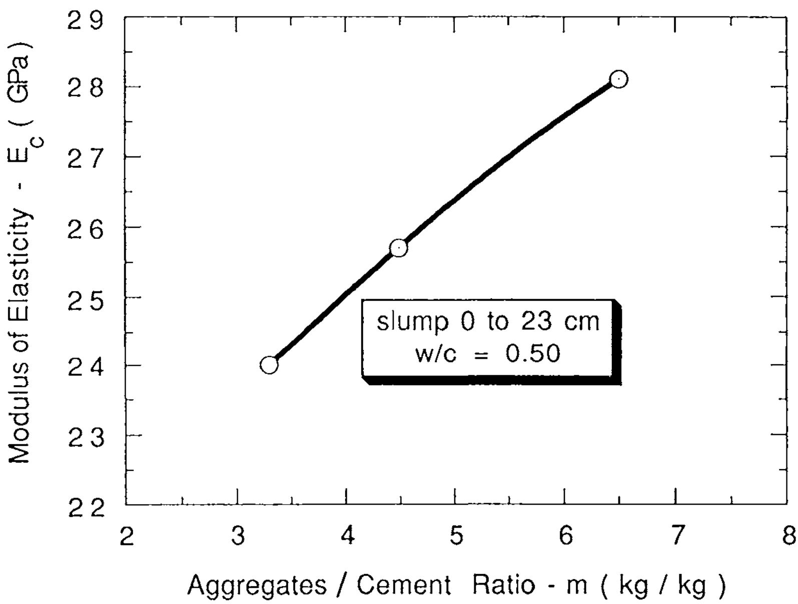

Fig. 13—Effect of aggregate-cement ratio on the modulus of elasticity for a constant water-cement ratio

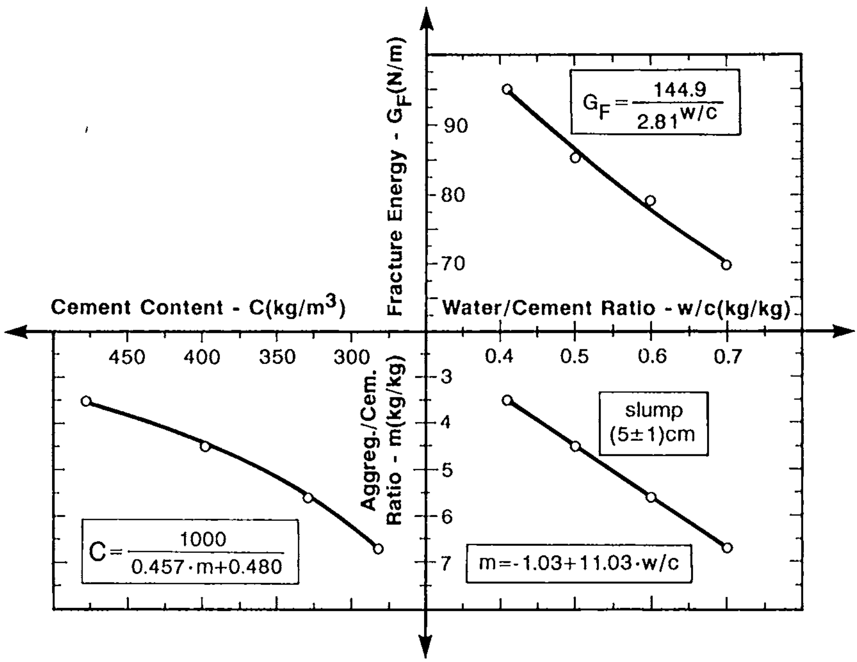

Fig. 14—Mix design nomogram for a given consistency of fresh concrete. Fracture energy as the design criterion

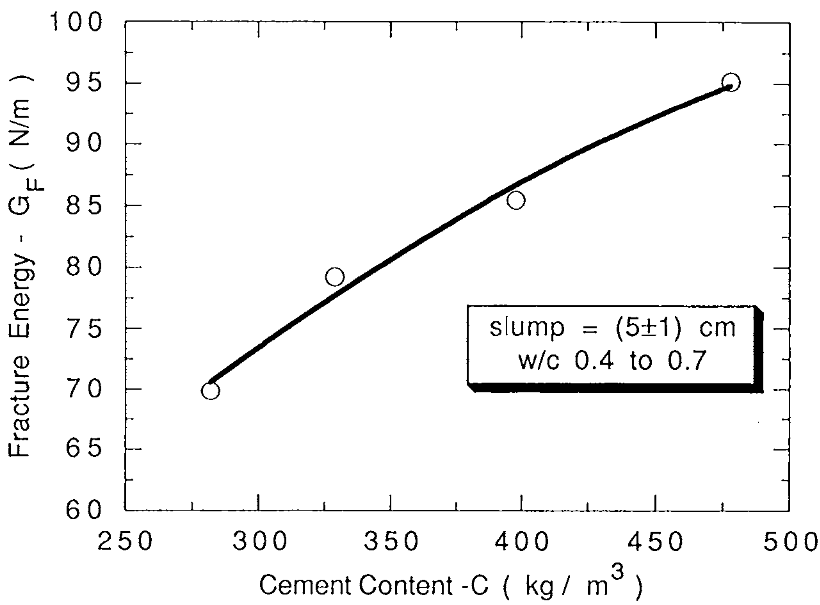

Fig. 15—Effect of cement content on the fracture energy for a constant consistency

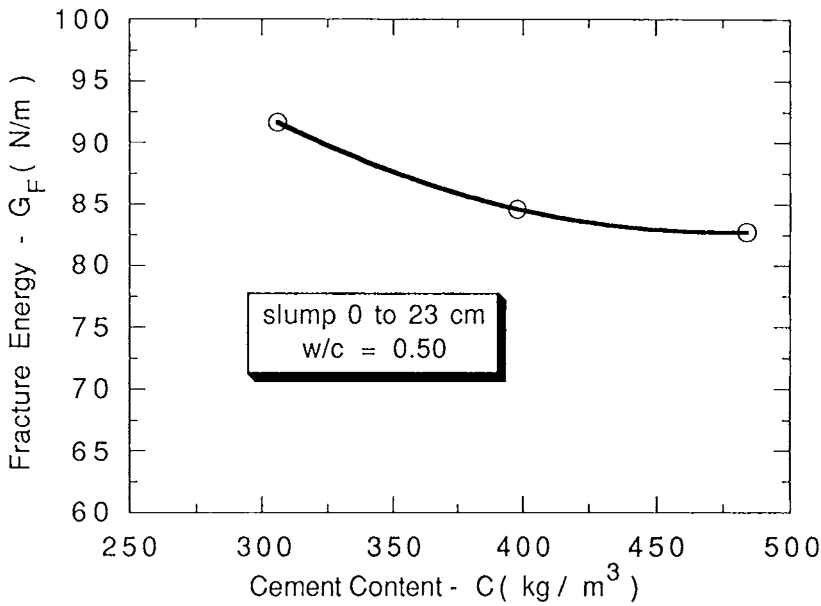

Fig. 16—Effect of cement content on the fracture energy for a constant water-cement ratio

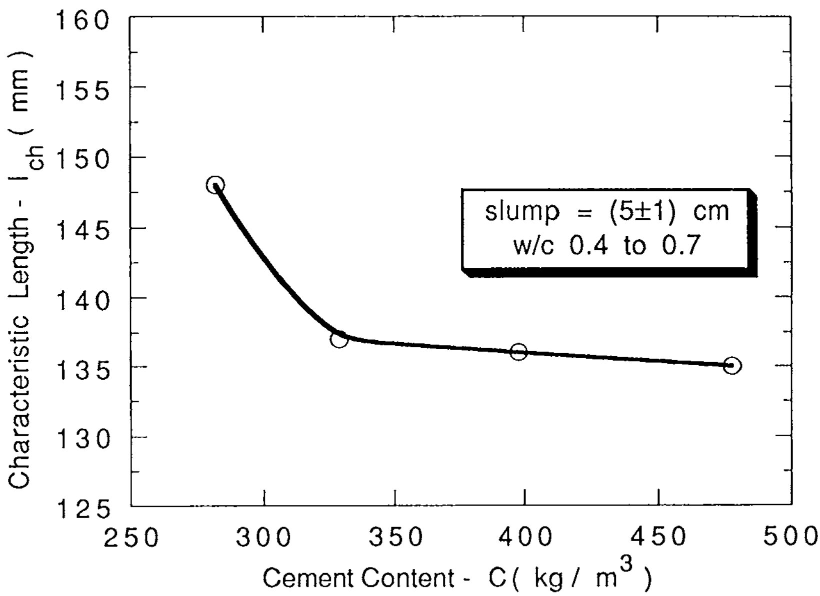

Fig. 17—Effect of cement content on the characteristic length for a constant consistency

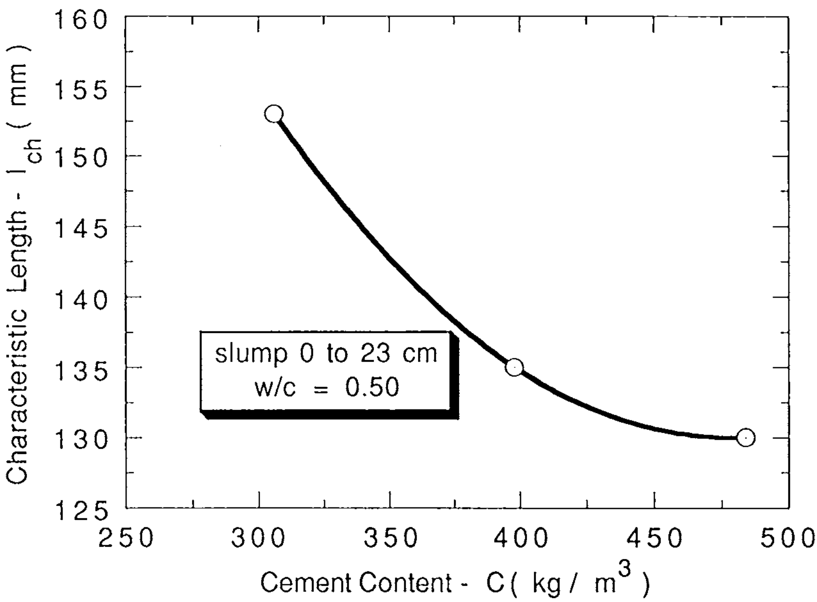

Fig. 18—Effect of cement content on the characteristic length for a constant water-cement ratio