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High-Performance Concrete Mixture Proportioning

by K.G. Sobolev and S.V. Soboleva

Synopsis: The report generalizes the results of wide range investigations of silica fume based superplasticized high- performance concrete. The rules of the strength and rheological behavior of cement - silica fume - superplasticizer systems are discussed. Usage of optimal superplasticizer to silica fume ratio (as 1:10) allows to obtain ultra-dense packing for super fluid cement paste and provides high-performance properties of concrete.

The mathematical models of fresh and hardened high-performance concrete based on processing and computerizing empirical results are created. The models provide a calculation of W/C required for the target compressive strength level up to 130 MPa as well as mixing water quantity for planning slump of 0 - 200 mm. For modelling purpose, concrete slump is considered as a function of aggregates proportioning, and volume and fluidity of cement paste.

This approach became a basis of proposed high- performance concrete mixture proportioning method. Further, developing and integration of the mathematical models created a new computer program for high-performance concrete mixture proportioning. The program provides a solution for wide range design and optimization projects. The results of the computer program estimation can be easily transferred to any 3- dimensional plotting or data base program for consequent processing and performing.

Keywords: compressive strength; high-performance concrete; mix proportioning; silica fume; slump; superplasticizers

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INTRODUCTION

At present, high-performance (HP) concrete is applied in construction projects worldwide [1,2]. This new type of concrete fast turned from laboratory investigation to practical utilization and became a part of the market. Based on recent developments in concrete technology, HP concrete is characterized by high level of properties such as workability, strength and durability. These advantages provided the large-scale cost saving in various unique projects.

The modern HP concrete technology is based on the concept of DSP (Densified System with Ultra Fine Particles) which includes the effective use of silica fume (SF) and superplasticizer (SP) combination to modify the cement system at very small W/C [3]. The use of SF fills space between cement particles and aggregate transition zone, as well as providing a high rate of pozzolanic reaction by forming low compacted C-S-H.

The computer based forecast and properties control is important to extend the application of HP concrete in the industry. There are various methods for the calculation of conventional concrete mixture proportions [4,5]. Generally, these methods are based on the fundamental functions such as water to cement ratio (Abrams-Bolimey-Feret' laws), the constancy of water demand (Lyse' law) and optimum aggregates proportioning (Faury-Bolomey-Fuller' laws) which determine mixtures with the desirable properties. These methods can be adjusted to create concrete mixtures, which a part of cement is replaced by mineral admixtures as fly ash or silica fume, and chemical admixtures such as plasticizers [6]. However, the problem of concrete mixture proportioning becomes more sophisticated for new generation of HP concretes. Although this problem has been a subject of a number of reports [7, 8], the solution of the problem of HP concrete mixture proportioning and optimization still exists. Most of existing HP concrete mixture proportioning methods are semi-analytical and usually provide aggregate proportioning and calculation of W/C via concrete compressive strength equation [6-8].

A computer based mixture proportioning system performing simulation and optimizing the wide range of the concrete mixtures requires an analytical method. The main postulates of methods which is sensitive to different admixture application were the subject of our previous paper [9].

To elucidate the importance of the modified cement system the present paper uses rheological behaviour as the universal and essential approach for making HP concrete. Analytical mixture proportioning will be used, which also recognizes the contribution of mathematical models based on empirical results.

EXPERIMENTAL PROGRAM

Materials

Normal portland cement (PC) and silica fume (SF) were used in the experimental program. The portland cement was characterized by the following Bogue's composition: C_3S - 64%, C_2S - 14%, C_3A - 4%, and C_4AF - 14%. The SF was presented as glassy microspherical particles with diameter of 0.1 - 0.2 micron. The physical properties and chemical analysis of the cement and silica fume are shown in Table 1.

Commercially available sulfonated naphthalene formaldehyde condensate (SNF) type superplasticizer was used as modifier in the experimental program.

Granite crushed stone with a maximum size of 20 mm and specific gravity 2.68 kg/m^3 was used as coarse aggregate. Locally available natural sand with fineness modulus 1.95 and specific gravity 2.62 kg/m^3 was used as fine aggregate. The grading of the aggregates are given in Table 2.

Test Procedure

The determination of the rheological characteristics, such as viscosity and shear stress of the modified cement systems was executed on rotary cylinder viscometer at various deformation rate of a system of 0.3566-11.4112 s^{-1}) in a time-range of 5-60 minutes.

The strength characteristics of the modified cement systems were determined in accordance with standard procedure of ASTM C 109 "Standard Test Method for Compressive Strength of Hydraulic Cement Mortar" and C 348 "Standard Test Method for Flexural Strength of Hydraulic Cement Mortar" at cement to sand ratio 1:1 on prisms-samples 4x4x16 cm. Steam curing at temperature 80 ^{0}C was used for accelerating the hardening of samples. The compressive strength of mortar at W/C=0.14 was adopted as a strength indicator of the system and used for the optimization of composition.

The calculation of concrete mix proportion was made by means of a special computer program in accordance with the absolute volume method. Components of a concrete mix were dosed by weight and mixed in a rotary mixer for 5 minutes. Workability of a concrete mix was determined as slump. The compressive strength of concretes was determined on 10 cm cube-samples after 1, 3, 7 and 28 days of normal hardening at 20 ^{0}C.

The experimental program has included around 70 compositions of modified cement systems and mortars, as well as more than 100 HP concrete mixtures. The experimental test results were used for the creation and calibration of mathematical models.

The rules of the polystructural theory of concrete were used for the creation of models of HP concrete. According to the polystructural theory, the properties of concrete were considered as a function of properties of macrostructure (as aggregates) and microstructure (as modified cement system).

The microstructural level was embodied the strength and rheological properties of the cement - silica fume - superplasticizer system. The mathematical regressions of strength and rheological behavior of the system were created by means of processing and computerizing of the empirical results. The mathematical models were processed as 2nd order polynomial equations by means of the specially designed computer program and for some parameters the logarithmic compression of data was applied. The 2nd order polynomial equation was used for calculation of the target function:

$$F(n) = \sum_{i=0}^{n} \sum_{j=i}^{n} b_{ij} * x_i * x_j \qquad (1)$$

where n - total amount of parameters

b_{ij} - polynomial equation coefficients

x_i , x_j - polynomial equation parameters and $x_0 = 1$.

The optimal aggregates proportioning was determined as minimal deviation from nominal grading curve. After verification tests optimal fine to total aggregate ratio was 0.35, and actual grading curve was close to gap grading proposed in reference [10].

The concrete compressive strength is determined as a function of W/C. The slump of concrete mix was considered as a function of the volume and shear stress of cement paste and aggregates proportioning.

TEST RESULTS AND MODELS PROCESSING

Rheological Behavior of Modified Cement Systems

It was observed that for PC-SF-SP system, increasing the SP dosage, from zero to some limited dosage SP_{lim}, provides significant reduction of shear stress at various SF contents. It was found that the optimal SP_{lim} dosage is connected to SF content, and it was determined as 10% of SF.

There is the plateau of a minimum shear stress at the SF content of 10 - 20% and the optimal SP dosage. These compositions provide the best packing of PC and SF particles. Replacement of even a small amount of PC by SF of 1 to 5% makes the system more dense as the SP presence increases the thickness of water layers between PC particles, which provides a reduction of viscosity. Thus, the best packing and minimum viscosity are reached at the optimum contents of SF from 10 to 20% (Fig. 1). Increasing of the SF contents above 20% leads to surplus of the small-sized fraction and replacing of PC particles, causing unpacking of a system and growth of shear stress.

The comparison of the rheological behavior of PC and the modified system at various W/C allows the evaluation of the effect of SF as microfiller or SF-SP-effect [9]. The limited fluidity of PC paste in the time-range of up to one hour is taking place at W/C=0.4, whereas it occurs for the modified system at W/C=0.3. The shear stress of the modified system at 5% of SF and W/C=0.25 are essentially higher than the ones at 15% of SF and W/C=0.2, which provides production of more fluid modified system at smaller W/C (Fig. 2).

The laws of the modified system rheological behavior were used for the production of concrete mixes with a constant workability, as well as for the determination of the optimum contents of SP and SF [9].

The mathematical model of the rheology was processed. The parameters of the structure such as SP dosage (SP, %), SF contents (SF, %), W/C (W/C), hydration time (T, min) and the deformation rate of the system (S_d, c^{-1}) were used as parameters. For all parameters, except SP dosage, the logarithmic compression of data was applied. The polynomial equation coefficients as per (1) are presented in Table 3.

The model allows calculating the dosage of SP or W/C as parameters for required shear stress for producting isorheological system (Table 4), as well as determining the rheological behavior of the system at certain composition (Fig. 1-4). The rheology model was used as a processing block in the main HP concrete mixture proportioning computer program.

Strength of Modified Cement Mortar

The test results of the system strength characteristics have confirmed the assumption that the optimum dosage of SP depends on the SF contents. The optimum SF contents in the system was found as 15%. For optimal composition, the compressive strength was of 136 MPa and flexural strength of 18 MPa at W/C=0.14 (Fig. 5-6).

It was observed that the strength of the investigated system depends only on W/C (Fig. 6). This assumption allows to determine a pozzolanic effect of SF as an equivalent of the used cement strength. The microfiller effect of SF can be stated as ability to essentially decrease (down to W/C=0.14) the water demand of the system.

The laws of the system strength behavior were used for optimization of binder composition [9]. The mathematical models of the strength were calculated. The parameters of the composition as SP dosage (SP, %) and SF contents (SF, %) were used as factors. The polynomial equation coefficients as per (1) are presented in Table 5.

The strength model allows the calculation of the optimum SP dosage and SF content to provide the required strength level (Fig. 5). The model was used as a processing block in the main HP concrete mixture proportioning computer program.

Properties of Fresh Concrete

Air contents of fresh concrete mixtures were varied from 1.9 to 2.4%, and the average amount of entraining air was 2.0%. No bleeding of the HP concrete was found.

It was determined that for the certain concrete mixtures, slump can be adjusted in a wide range of 40 to 200 mm by variation of the SP dosage from 4 to 18% of SF. The constant slump value can be provided for different SF contents of 5 to 25%, at the optimal SP dosage and fixed water content. The increasing of cement content, at fixed water content, leads to slump increase (by 20-40 mm) due to growth of the cement paste volume and the compensation of the viscosity (Fig. 7). The main laws of the concrete mixture slump behavior showed good correlation to the modified cement rheology (Fig. 1-4).

The definition of the concrete mixture slump laws was proposed as the function of the aggregates proportioning, rheological characteristic and the volume of the cement paste. The slump model with parameters as fine to total aggregates ratio (r), shear stress (S_s, Pa) and volume of the cement paste (V_{cp}, dm^3) was processed. The polynomial equation coefficients as per (1) are presented in Table 6.

The slump model can be used for predicting the slump for wide range of HP concrete mixtures due to the independence on admixtures dosage (Fig. 7). The model was used as a processing block in the main HP concrete mixture proportioning computer program.

Compressive Strength of the HP Concrete

The increasing of the SP dosage from 8 to 18% of SF decreases W/C from 0.31 to 0.26 and increased the concrete 28- day compressive strength from 86 to 97 MPa. The maximum compressive strength of 91 MPa was reached at the 15%-SF content with fixed cement content of 400 kg/m^3. The lower strength value 90 MPa was provided at 10 and 20% of SF. The HP concrete strength behavior maintains relationship to the strength of modified cement mortar (Fig. 5).

The reduction of W/C from 0.32 to 0.19 increased the compressive strength of the concrete and produced super- high strength HP concrete with compressive strength of 135 MPa. It was found that 28- day compressive strength of investigated concretes could be presented as function of W/C for the wide range of compositions (Fig. 8).

The experimental data were used for HP concrete strength model processing. The model was presented as the following equation:

$$f_{28} = 331.26 * e^{-5.0018W/C} \qquad (2)$$

The strength model was used for calculation of W/C for the target HP concrete compressive strength level in the range of 50-130 MPa, and also as a module of the main HP concrete mixture proportioning computer program.

PROPOSED HP CONCRETE MIXTURE PROPORTIONING METHOD

The flow chart procedure of the proposed method of HP concrete mixture proportioning is given in Fig. 9. The analytical method has been used for the simulation and optimization of the wide range of concretes as well as the basic of the HP concrete mixture proportioning system. The contribution of different admixtures on rheological behavior of the system can be measured manually or calculated by means of the rheological model. The effect of the rheological parameters on mixtures at different W/C, SF or SP dosages, on the concrete slump can be adjusted, by the corresponding calculation of the cement paste volume.

The computer based HP concrete mixture proportioning system based on mathematical models of processed empirical results was established provides a solution for a wide range of design and optimization projects. The results of the computer program computations presented by means of a 3-dimensional plotting program are summarized in Fig. 1-5, 7, 10, 11. The examples of the computer program processing of HP concrete mixture proportioning are presented in Table 7. The effect of HP concrete properties on total cement content and mixture cost are shown in Fig. 10-11.

CONCLUSIONS

1. The computer mathematical models can simulate the rheological behavior of the modified cement system. The rheological model enables the calculation of the dosage of SP or W/C as parameters for obtaining required shear stress in the isorheological system. The strength models can be used to determination of the optimum SP dosage and SF content, at the required compressive strength level of mortar.
2. The concrete mixture slump can be presented as a function of the shear stress and volume of the cement paste and the aggregates proportioning. The HP concrete strength model can be supplied in the form of exponential equation. The strength model is applicable for calculation of W/C for the target compressive strength level of HP concrete in the range of 50-130 MPa.
3. The proposed analytical method of HP concrete mixture proportioning can perform simulation and optimization of a wide range of concrete mixtures. The contribution of the different admixtures on rheological behavior of the system can be measured or calculated by means of the rheological model. The effect of the rheology on the

concrete slump can be adjusted by corresponding calculation of the cement paste volume. The developed models can be used for HP concrete computer - based mixture proportioning system.

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TABLE 1—PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF CEMENT AND SILICA FUME

	Portland Cement	Silica Fume
Physical Properties		
Surface Area, m2/kg	350	20000
Specific Gravity, kg/m3	3.15	2.21
Setting Time, hr:min		
- Initial	2:10	
- Final	3:40	
Compressive Strength, MPa		
- 1 day	15.8	
- 3 days	34.2	
- 7 days	44.3	
- 28 days	55.2	
Chemical Analysis		
SiO_2	22.1	90.2
Al_2O_3	4.86	1.7
Fe_2O_3	4.92	0.4
CaO	66.87	2.1
MgO	0.42	1.7
Na_2O	0.15	0.7
K_2O	0.15	0.7
SO_3	4.03	0.5
L.O.I.	1.64	2.5

TABLE 2—GRADING OF AGGREGATES

Aggregate Type	Passing, % @ Mesh Width, mm							
	0.14	**0.31**	**0.63**	**1.25**	**2.50**	**5.00**	**10.00**	**20.00**
Fine	3.98	35.46	77.52	91.01	96.83	100.00	100.00	100.00
Coarse	0	0	0	0	0.67	2.68	35.90	100.00

TABLE 3—THE POLYNOMIAL EQUATION COEFFICIENTS

Description		Polynomial Equation Coefficients b_{ij} for i					
X_j	j	0	1	2	3	4	5
-	0	9230.17	-918.00	-1042.29	-5441.18	765.48	280.26
ln(10SF)	1		-7.69	88.32	313.26	-16.44	-17.68
SP/10	2			2.59	253.17	-28.80	6.28
ln(50W/C)	3				814.47	-262.99	-95.02
ln(2T)	4					14.07	11.51
ln(10S$_d$)	5						7.58

TABLE 4—PARAMETERS FOR PRODUCTION OF ISORHEOLOGICAL SYSTEMS

Composition of Modified System, %		Required W/C for Providing of Shear Stress, Pa				
Silica Fume	*Superplasticizer*	5	10	50	100	300
5	8	0.431	0.424	0.386	0.354	0.278
5	10	0.427	0.419	0.379	0.346	0.271
5	12	0.421	0.413	0.371	0.338	0.264
10	8	0.360	0.356	0.327	0.301	0.240
10	10	0.360	0.355	0.324	0.298	0.235
10	12	0.360	0.355	0.321	0.293	0.230
15	8	0.314	0.311	0.290	0.269	0.217
15	10	0.314	0.311	0.288	0.267	0.213
15	12	0.314	0.311	0.286	0.263	0.209
20	8	0.282	0.279	0.262	0.245	0.199
20	10	0.282	0.279	0.261	0.243	0.196
20	12	0.282	0.279	0.259	0.241	0.193

TABLE 5—THE POLYNOMIAL EQUATION COEFFICIENTS OF THE MODIFIED SYSTEM STRENGTH MODEL

Description		Polynomial Equation Coefficients b_{ij} for i		
X_j	j	0	1	2
-	0	95.510290	3.706451	1.280670
SF	1		-0.238036	0.267467
SP	2			-0.210507

TABLE 6—THE POLYNOMIAL EQUATION COEFFICIENTS OF THE SLUMP MODEL

Description		Polynomial Equation Coefficients b_{ij} for i			
X_j	j	0	1	2	3
-	0	-2246.554000	-0.463865	8.417213	47.43504
S_s	1		0.000013	0.000845	-0.00528
V_{sp}	2			-0.007401	-0.06609
r	3				-0.34795

TABLE 7—HP CONCRETE MIXTURE PROPORTIONING

	SF *5*	SF *10*	SF *15*	SF *20*
Mixture Proportions, kg/m3				
Cement	426	449	468	478
Silica Fume	22	50	83	120
Total Cement and Silica Fume	448	499	550	598
Superplastisizer	2.2	5.0	8.3	12.0
Water	153	142	132	121
Coarse Aggregate	1169	1155	1136	1119
Fine Aggregate	630	622	612	603
Mixture Parameters				
Silica Fume, %	5	10	15	20
W/C	0.342	0.284	0.239	0.203
Shear Stress, Pa	97	132	187	265
Cement Paste Volume, dm^3	298	307	318	327
Fine to Total Aggregates Ratio	0.35	0.35	0.35	0.35
Fresh Properties				
Slump, mm	100	100	100	100
Fresh Unit Weight, kg/m3	2402	2422	2438	2453
Air Content, %	2.5	2.5	2.5	2.5
Mechanical Properties				
Compressive Strength, MPa				
- 1 day	16.8	24.1	34.4	45.1
- 3 days	28.6	42.2	63.0	84.9
- 7 days	50.1	67.2	84.8	102.5
- 28 days	60.0	80.0	100.0	120.0
Concrete Cost				
Concrete Mixture Cost, US $	46	54	63	73

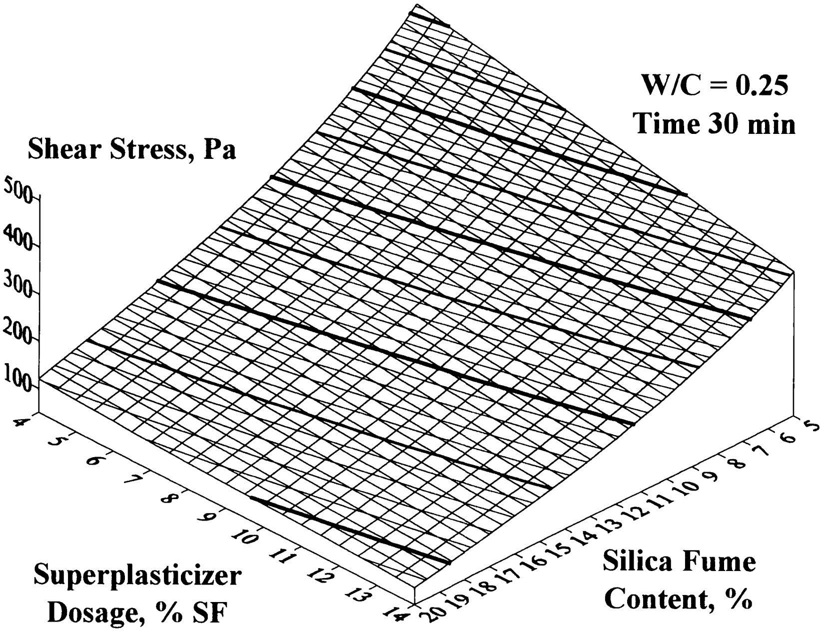

Fig. 1—Rheological behavior via composition

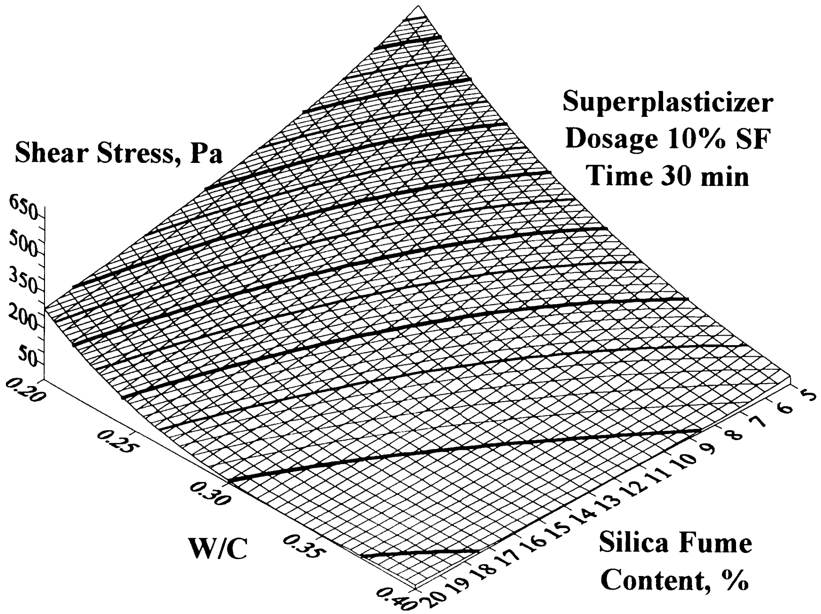

Fig. 2—Effect of silica fume and W/C on rheological behavior

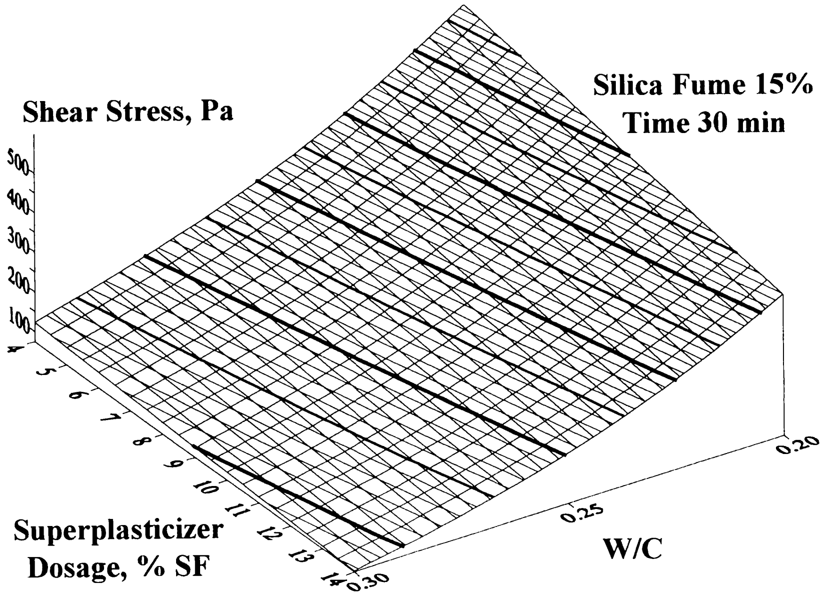

Fig. 3—rheological behavior via W/C and superplasticizer dosage

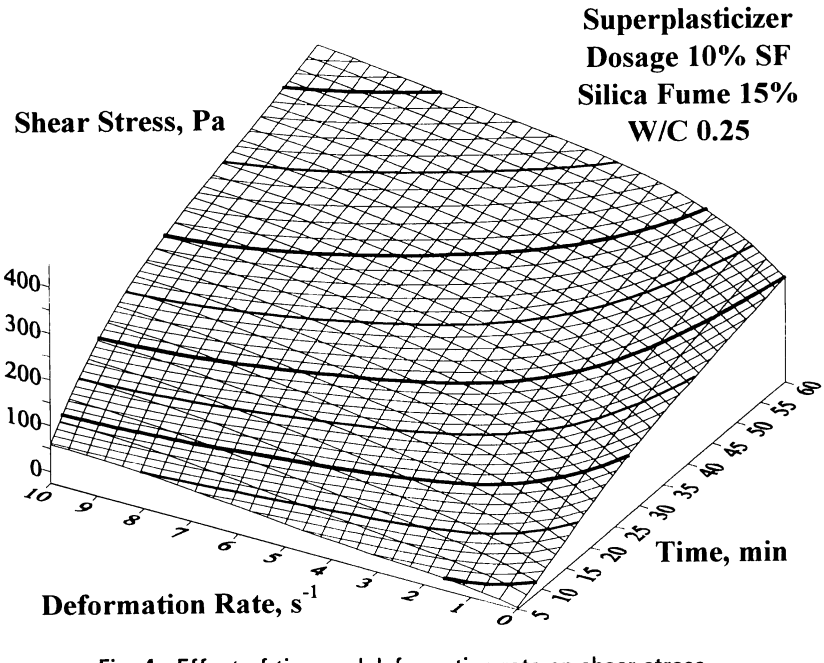

Fig. 4—Effect of time and deformation rate on shear stress

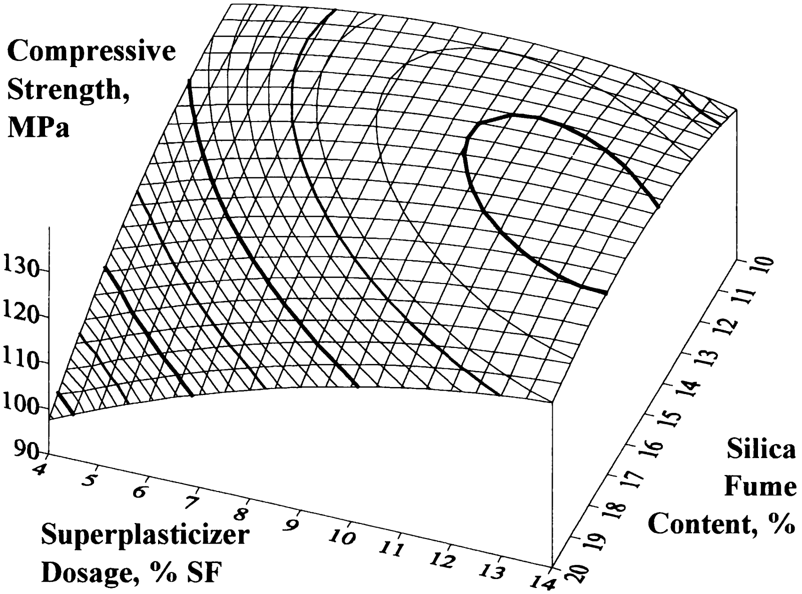

Fig. 5—Mortar compressive strength via composition

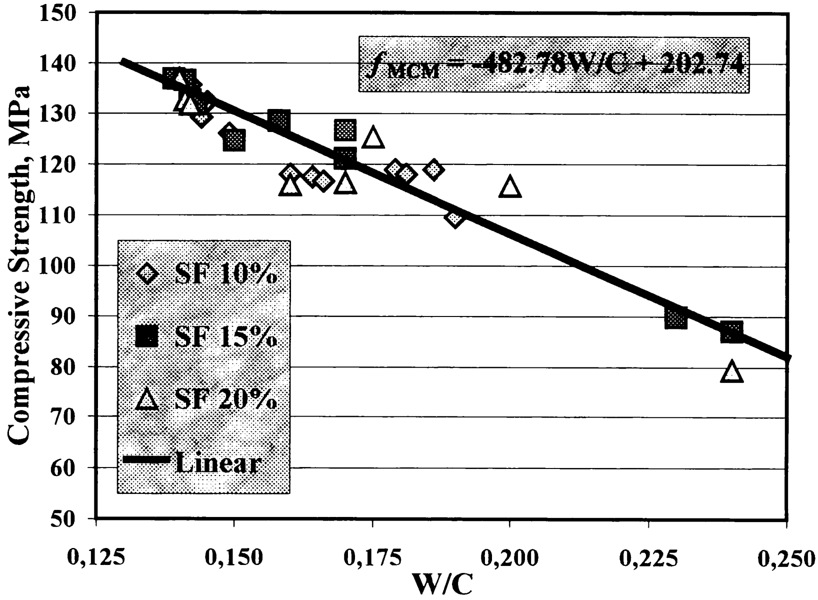

Fig. 6—Compressive strength of modified cement mortar

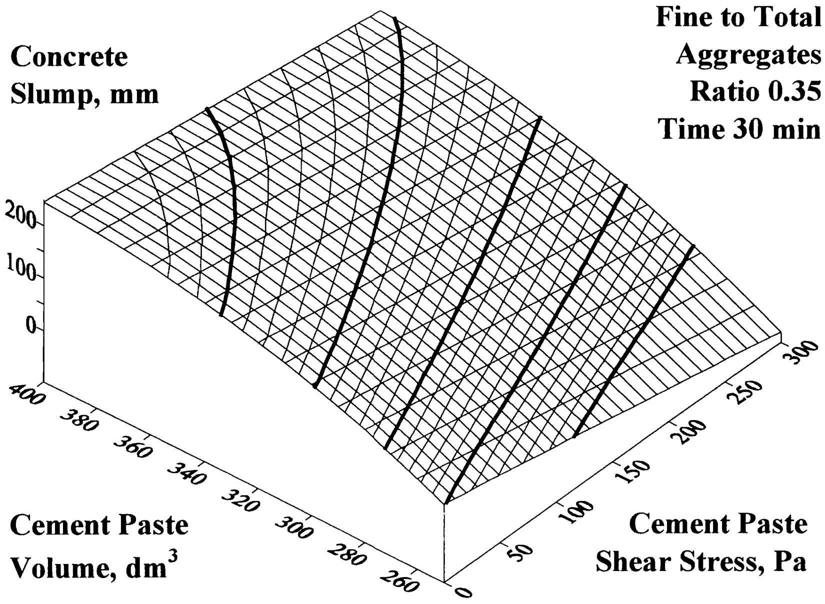

Fig. 7—Concrete slump as function of shear stress and volume of the cement paste

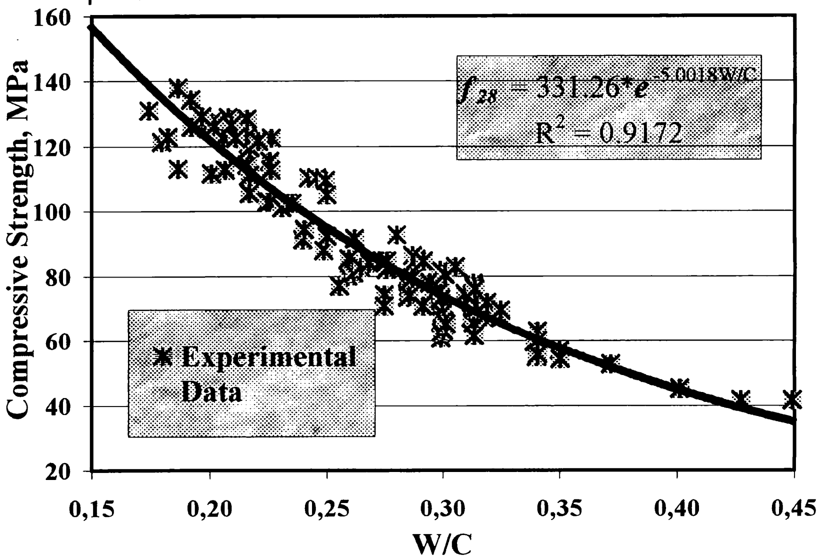

Fig. 8—HP concrete compressive strength

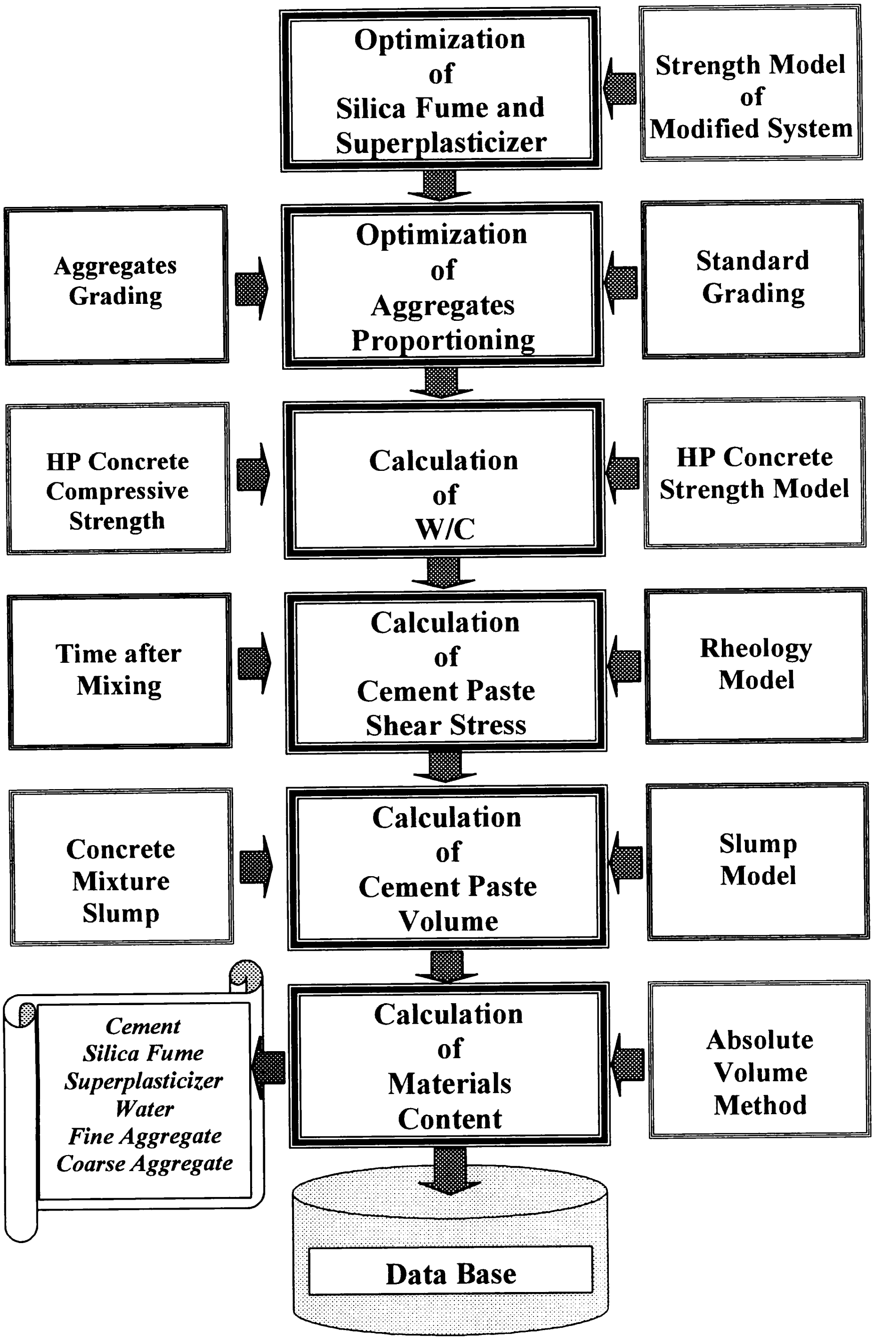

Fig. 9—Flow chart of HP concrete mixture proportioning

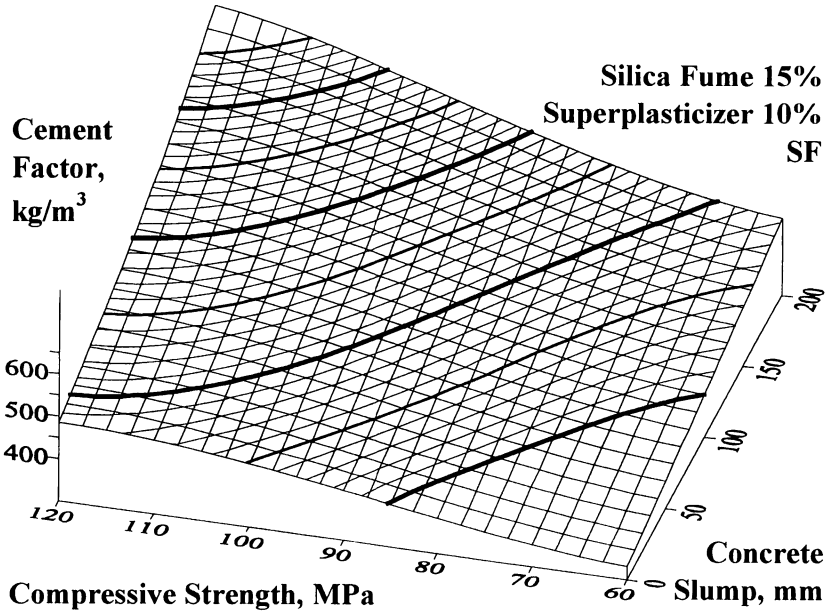

Fig. 10—Cement content via HP concrete properties

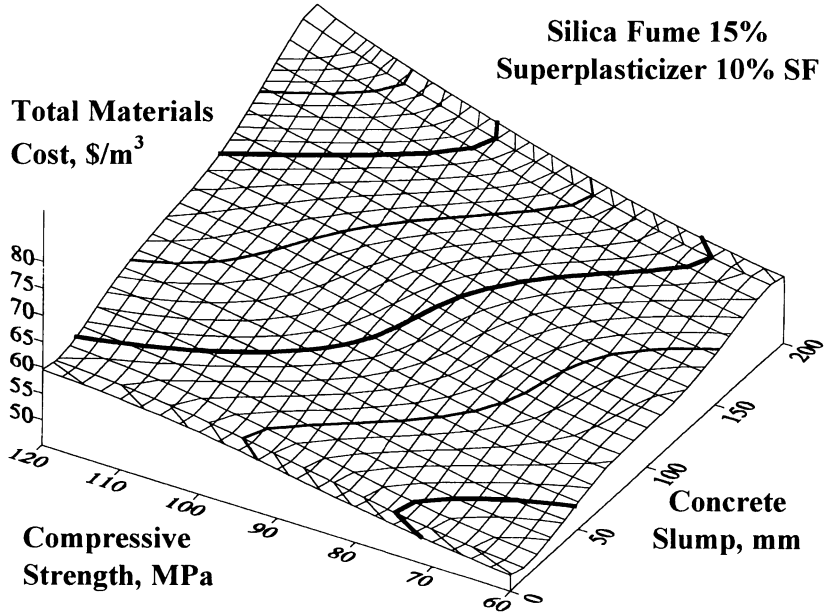

Fig. 11—Effects of HP concrete properties on material costs