Pergamon

Cement and Concrete Research, Vol. 25, No. 7, pp. 1480-1490, 1995

0008-8846/95 $9.50+.00

0008-8846(95)00142-5

AN OPTIMIZATION OF FLY ASH QUANTITY IN CEMENT BLENDING

Lj. Fisang*, M. Djuric**, R.M. Neducin**, J. Ranogajec** and A.Mihajlov***

* Beocin Cement Factory, R&D, 21300 Beocin, Yugoslavia
** University of Novi Sad, Faculty of Technology
21000 Novi Sad, Bul. Cara Lazara 1, Yugoslavia
*** Federal Ministry of Environment
11070 Beograd, Bul.Lenjina 2, Yugoslavia

(Refereed)
(Received December 13, 1994)

ABSTRACT

The Two Goal Approach was applied to the maximization of fly ash quantity (i.e. minimization of energy consumption) in producing cement of acceptable mechanical characteristics. Mathematical model of the optimization problem consists of two objective functions; a requirement concerning ash quantity and a condition upon particular mechanical property. All data were obtained by a kind of the Mixture Design experiments, i.e. mixtures were made, by blending of various quantities of usually used components with fly ash , and their characteristics were determined by the standardized methods. The procedure was applied to a few chosen examples and optimal quantities of fly ash were suggested.

Introduction

Fly ash appears as a byproduct from fluidized bed combustion which occurs in each steam generator of thermal power plants . Quantity of ash is so enormous that causes serious problems whose elimination is closely related to the protection of the environment and minimization of its pollution. Fortunately , thanks to many innovative spirits and scientists , the problem is successfully solved and many possible applications have been suggested; among others, in the cement and concrete field [1]. Here, fly ash is used not only with the aim to reduce growing quantity of waste material but also in order to modify some cement properties [2,3] . Namely, ash can play quite active role in which an advantage is taken of so called pozzolanic activity.

Very often, fly ash does not suit as a raw material for cement manufacturing, because of high content of some undesirable elements (e.g. sulfur). In that case, a method should be applied (and a computational technique) for adjusting raw mixture composition [4].

Essential aspect of fly ash application is optimization of its quantity which strongly depends on ash properties. The fact that ash appears as a component does not change principles of mathematical modelling and optimizing. So, well known techniques and procedures [5-8] can be modified and used for solving an ash- problem. This paper offers such a modification.

Data About Investigated System

Ordinary Portland Cement and three types of ashes: A (low lime, obtained at 1200 °C), B (high lime, obtained at 1200 °C) and C (melted ash, obtained at 1600°C) were used (for blending of final products) as raw materials.

Their chemical composition, pozzolanic activity, surface area, size distribution and other properties were determined, by standard methods and can be found in the paper [9]. As for mechanical properties of applied cement, a distribution of results (acquired by measurements of flexural strength and compressive strength) can be seen in Fig.1, while the mean values are given in Table 1.

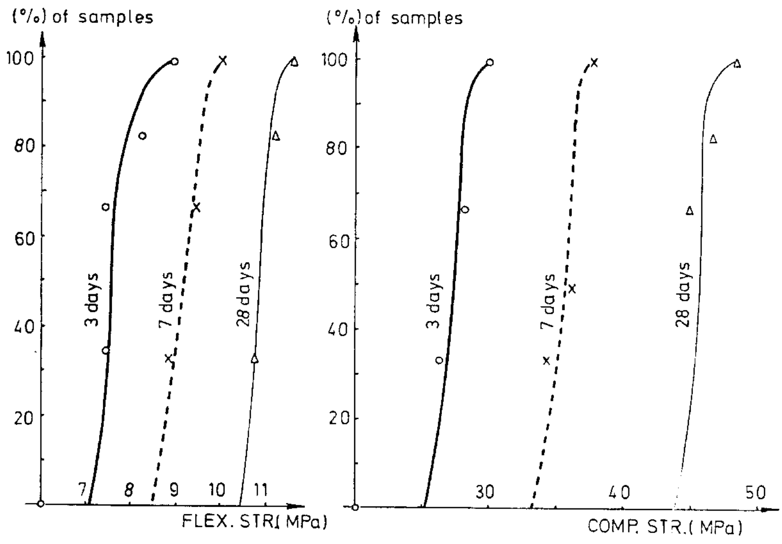


Fig.1. Measured Mechanical Characteristics of Cement

Table 1. Means of Measured Mechanical Characteristics for Cement and Particular Mortar Mixtures

No.	Ash Quantity	Flexural Strength (MPa)			Compressive Strength (MPa)		
		3 days	7 days	28 days	3 days	7 days	28 days
1	0 wt%	7.82	9.42	11.08	28.25	36.11	45.68
2	15 wt% A	5.38	8.46	10.59	17.16	32.30	46.99
3	20 wt% A	7.17	8.91	10.60	23.76	31.75	40.50
4	30 wt% A	6.00	7.63	9.90	19.82	27.1	36.46
5	15 wt% B	5.83	8.77	10.74	19.21	33.72	45.44
6	20 wt% B	7.58	9.32	11.04	25.61	34.31	42.11
7	30 wt% B	5.50	8.06	10.35	16.80	29.00	40.48
8	15 wt% C	5.84	8.32	10.27	20.63	32.79	44.80
9	20 wt% C	7.23	8.69	11.06	25.78	32.48	43.41
10	30 wt% C	5.61	7.07	9.47	18.83	25.44	36.08

After analyzing of raw materials , they were used in blending of mortar mixtures (EN 196-1/92), whose mechanical properties were tested by nine series of experiments (for each particular property), in accordance with full factorial design; i.e.two factors (wt.% of fly ash- denoted by x_1 and period of curing time- denoted by x_2) were measured at three levels,so that: $N=3^2=9$ experiments were required.

Distributions of measured strengths (of all the mixtures) are presented in Figs. 2 - 6 , while relevant statistical parameters (standard deviation and standard error) were determined either. Both were used in checking whether the suggested mean values (in Table 1.) are representative enough . A positive answer was obtained in almost all cases.

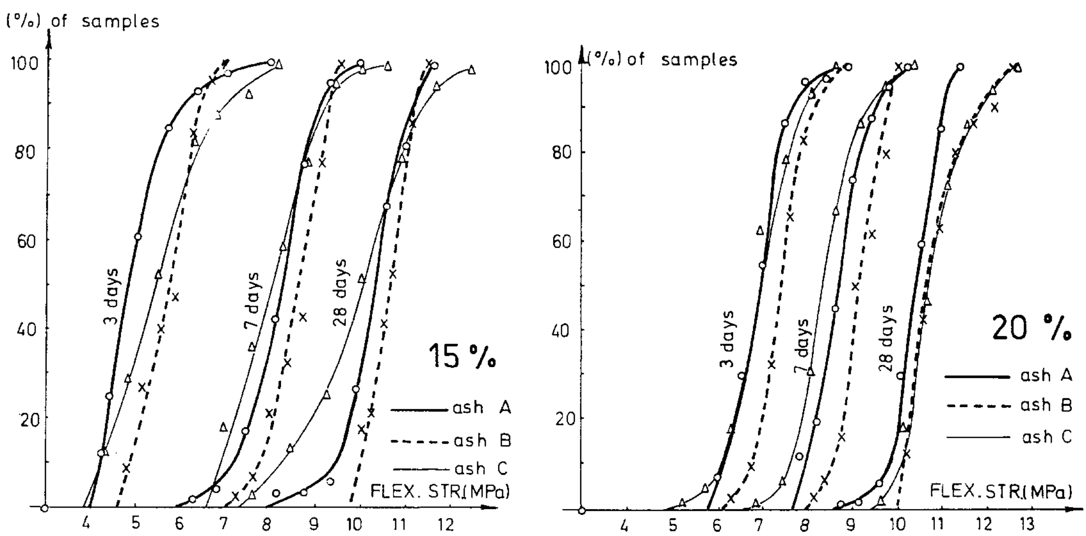


Fig.2. Measured Flexural Strength of Mixtures With 15 wt% of Ash and 20 wt% of Ash

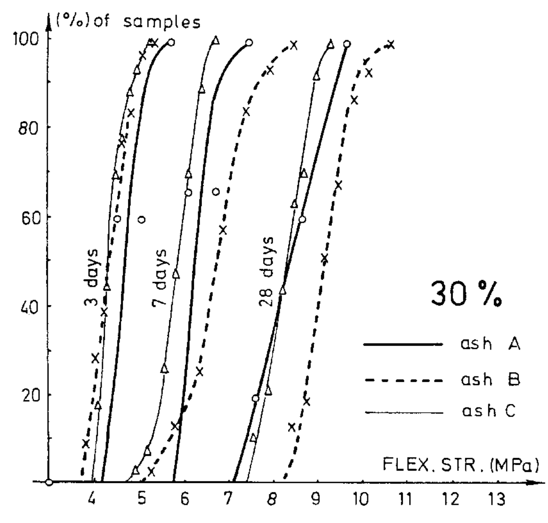


Fig.3. Measured Flexural Strength of Mixtures With 30 wt% of Ash

Mathematical Model for Mechanical Characteristics

To investigate the system behaviour , nine series of experiments were carried out . This all allows developing of regression equation which takes into account not only linear terms but the interaction terms as well as the terms of higher order . A few alternatives were tested and the one with the minimal value of σ (squared sum of deviations - errors among measured and calculated sample characteristics) was selected:

$$y=b_1+b_2x_1+b_3x_2+b_4x_1x_2+b_5x_1^2+b_6x_2^2+b_7x_1^2x_2+b_8x_1x_2^2 \qquad (1)$$

The coefficients of the polynomial (1), for both flexural strength and compressive strength and three different types of ashes , were determined by the

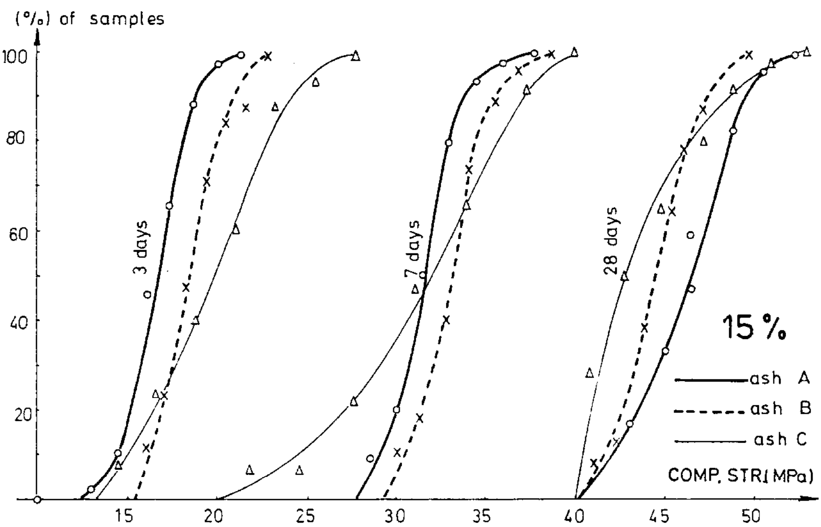


Fig.4. Measured Compressive Strength of Mixtures With 15 wt% of Ash

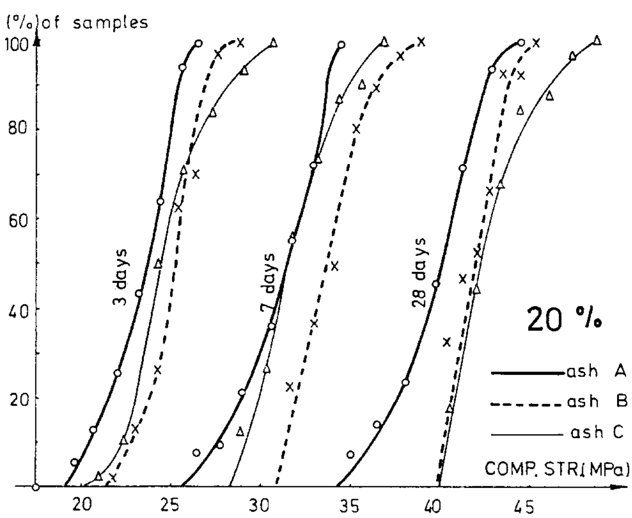


Fig.5. Measured Compressive Strength of Mixtures With 20 wt% of Ash

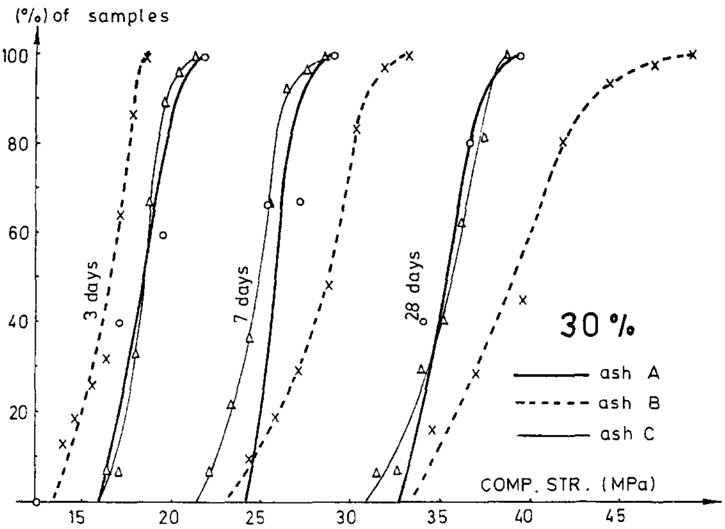


Fig.6. Measured Compressive Strength of Mixtures With 30 wt% of Ash

Regression Analysis and presented in Table 2. The fact that the "response surface" (1) depends on only two variables allows its graphical presentation as it can be seen in Figs. 7-10 for all examined (mechanical) properties.

Finding an Absolute Optimum

Mathematical model of system behaviour (in terms of flexural strength and compressive strength) can be used as an objective function, whose extreme (maximum) corresponds to the (absolutely) optimal quantity of fly ash and period of curing time . The optimization model should contain a restriction upon the minimal amount of flying ash:

$$x_1 \geq 15 \qquad (2)$$

Otherwise, there is a risk that this component might be neglected during

Table 2. Coefficients of Equation (1)

Coef.	Flexural Strength			Compressive Strength		
	Ash A	Ash B	Ash C	Ash A	Ash B	Ash C
b_1	-11.4788	-10.4011	-7.6466	-49.9727	-47.8691	-35.6442
b_2	1.3827	1.4080	1.1318	5.2293	5.6441	4.5869
b_3	1.8005	1.3248	1.1461	9.6186	7.5042	6.4788
b_4	-7.1E-2	4.4E-2	-3.0E-2	-0.4317	-0.3080	-0.2304
b_5	-2.8E-2	-3.2E-2	-2.4E-2	-0.1029	-0.1275	-9.8E-2
b_6	-3.7E-2	-2.4E-2	-2.7E-2	-0.1685	-0.1174	-0.1321
b_7	8.8E-4	8.8E-4	2.2E-4	6.0E-3	6.1E-3	2.6E-3
b_8	9.1E-4	1.5E-4	6.2E-4	4.1E-3	8.8E-4	3.1E-3
σ	0.1724	0.3226	0.1278	3.4999	4.7892	2.6123

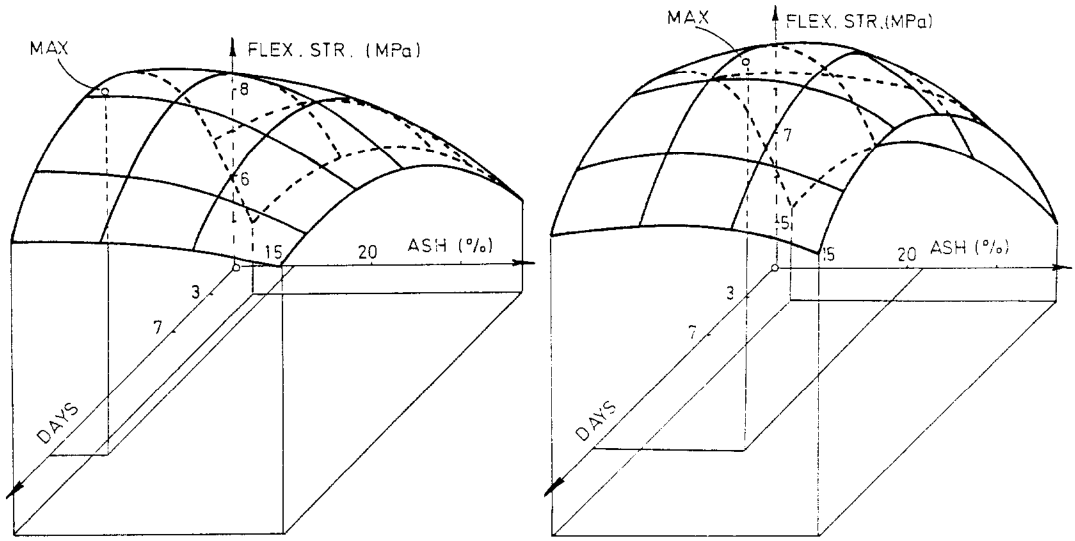


Fig.7. Flexural Strength Response Surfaces of Samples With Ash A and Ash B

blending procedure . Transformed into equation , inequality (2) becomes following form:

$$g=x_1+x_3^2-15=0 \qquad (3)$$

where x_3 is an additional variable.

Incorporating of the restriction into the objective function (through using the Lagrange multiplier- x_4), modifies it into the form:

$$F=y+x_4g=$$

$$=b_1+b_2x_1+b_3x_2+b_4x_1x_2+b_5x_1^2+b_6x_2^2+b_7x_1^2x_2+b_8x_1x_2^2+x_4(x_1+x_3^2-15) \qquad (4)$$

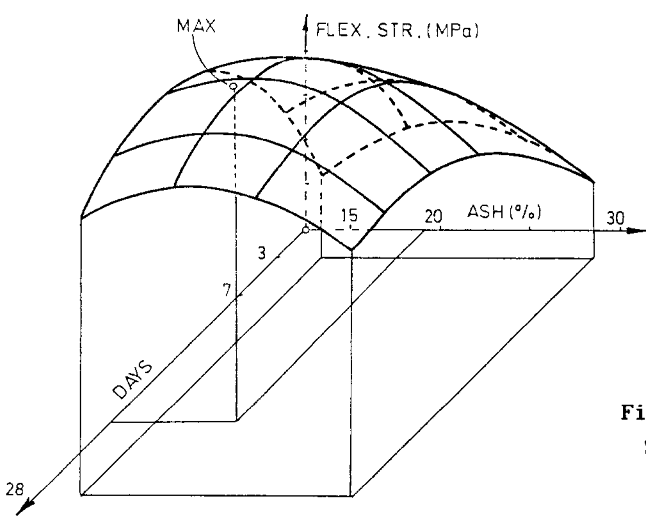


Fig.8. Flexural Strength Response Surface of Samples With Ash C

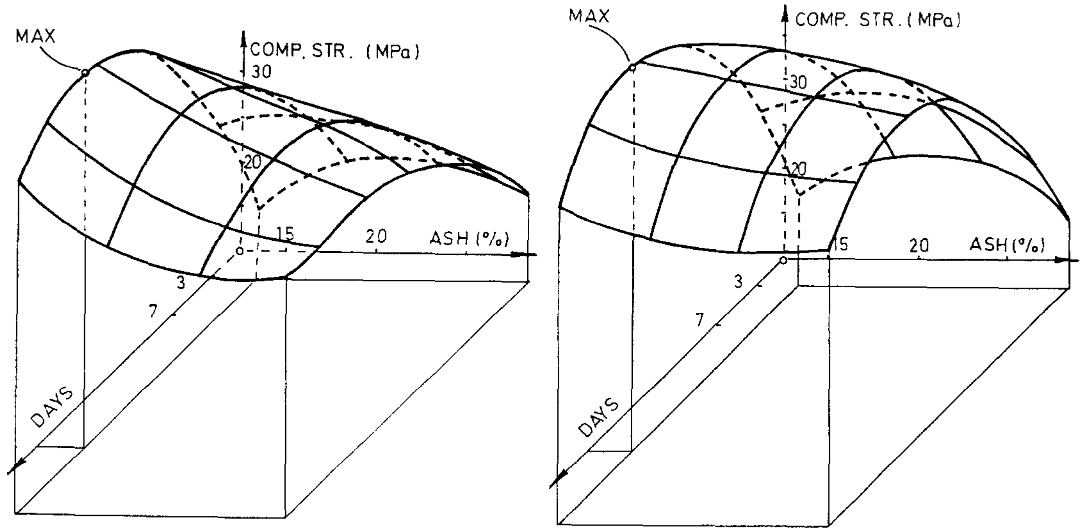


Fig.9. Compressive Strength Response Surfaces of Samples With Ash A and Ash B

A mathematical basis for finding a maximum of this function is:

$$\frac{\partial F}{\partial x_1} = b_2 + b_4 x_2 + 2b_5 x_1 + 2b_7 x_1 x_2 + b_8 x_2^2 + x_4 = 0$$

$$\frac{\partial F}{\partial x_2} = b_3 + b_4 x_1 + 2b_6 x_2 + b_7 x_1^2 + 2b_8 x_1 x_2 = 0 \qquad (5)$$

$$\frac{\partial F}{\partial x_3} = x_4 - 2x_3 x_4 = 0 \quad , \qquad \frac{\partial F}{\partial x_4} = x_1 + x_3^2 - 15 = 0$$

System of equations (5), solved by any of numerical methods, gives (absolutely) optimal values for independent variables. In our particular case,-

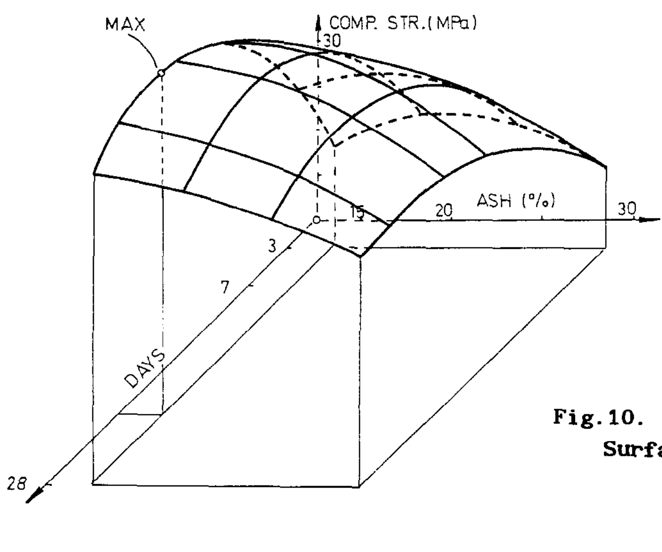


Fig.10. Compressive Strength Response Surface of Samples With Ash C

calculated (absolute) optimums have values as presented in Table 3. as well as in Figs. 7-10.

Finding a Solution in Accordance with Standard

Analysis of results obtained by the optimization procedure shows two facts ; (absolutely) optimal quantity of flying ash remains at rather low value (in the case of compressive strength it takes minimum) and all (absolutely optimal) mechanical characteristics are higher than the values required by standard, for the examined type of product (see Table 4). Therefore, there is a reason to increase ash quantity (as to decrease total cost of product). It can be done by obeying two goals (at the same time), during the optimization procedure [8].

Table 3. Absolute Optimums for Mechanical Characteristics of Mixtures

No	Additional Substance	Mechanical Characteristic	ABSOLUTE OPTIMUM x_1 (wt%)	x_2 (days)	y (MPa)
1	Ash A		15.7	19.7	12.20
2	Ash B	Flexural	20.9	18.9	12.66
3	Ash C	Strength	19.4	20.6	11.77
4	Ash A		15	21	52.44
5	Ash B	Compressive	15	20.4	51.58
6	Ash C	Strength	15	21	49.03

Table 4. Values of Mechanical Characteristics Required by Standard JUS B.C1.011 [10]

No.	Type of Cement	Flexural Strength (MPa)			Compressive Strength (MPa)		
		3 days	7 days	28 days	3 days	7 days	28 days
1	25	-	2.5	4	-	10	22
2	35 } S	-	3.5	5	-	14	31
3	35 } B	3	-	5	14	-	31
4	45 } S	3	-	5.5	14	-	40
5	45 } B	3.5	-	5.5	18	-	40

One goal can be formulated by a requirement:

$$x_1 \Rightarrow \max \qquad (6)$$

which is equal to the demand that energy cost remains at a minimum. Obviously, the greater ash quantity the smaller energy consumption (in the cement-clinker- sintering process), per unite of product.

The other goal should express a need for blending cements as flexural (and as hard) as possible:

$$F \Rightarrow \max \qquad (7)$$

This two goals are opposite, i.e. an increase of ash quantity contributes mostly to a decrease of mechanical characteristics of product (especially in the case of compressive strength).

The algorithm of the Two Goal Optimization Procedure should consist of following steps:

STEP 1. Adopting of initial value of ash quantity in the product;

STEP 2. Calculating of mechanical characteristic;

STEP 3. Comparison of calculated characteristic with the value specified by actual standard and ending the procedure when it drops below the standard one;

STEP 4. Continuation of optimization by increasing of ash quantity, for a small amount, and repeating of the procedure from the step 2.

Results of such a procedure are presented in Fig.11. It is obvious (for investigated examples) that neither of mechanical characteristics drops below standard value,for the whole interval of ash quantities; so that maximal amount (30 wt%) can be applied without braking standard requirements.

Discussion of Results and Conclusion

Before the optimization procedure was performed , usual statistical methods were used for checking following important things:

-whether the ash adding significantly changes mechanical characteristics of pure cement,
-whether the increase of ash quantity in the mixture (product) significantly influences its mechanical characteristics and
-how different types of ashes influence product quality.

Conclusions were made by comparing the means of following samples:

-pure cement and mixtures with minimal amount of ash,
-mixtures with different amounts of ash and
-mixtures with the same amount but different types of ashes.

The comparison was made by applying Student's t- test. As additional, Fisher's test was employed either. They helped in drawing the conclusions:

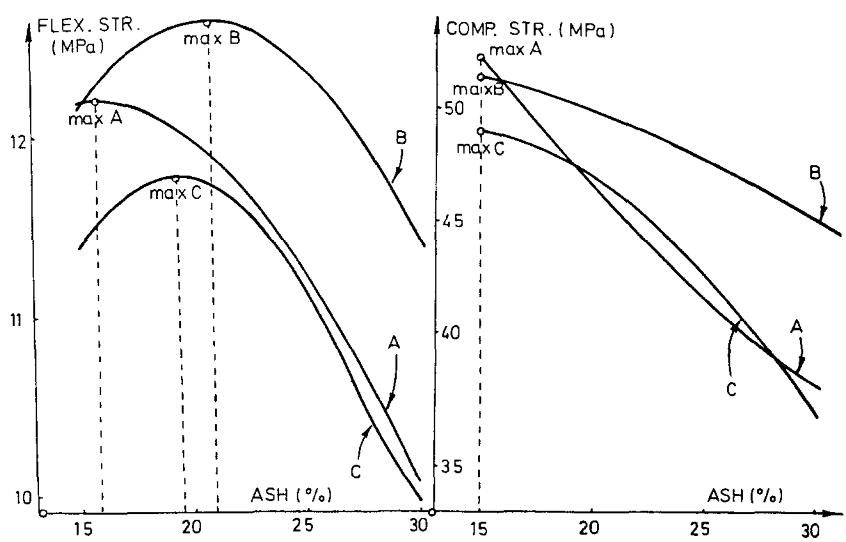


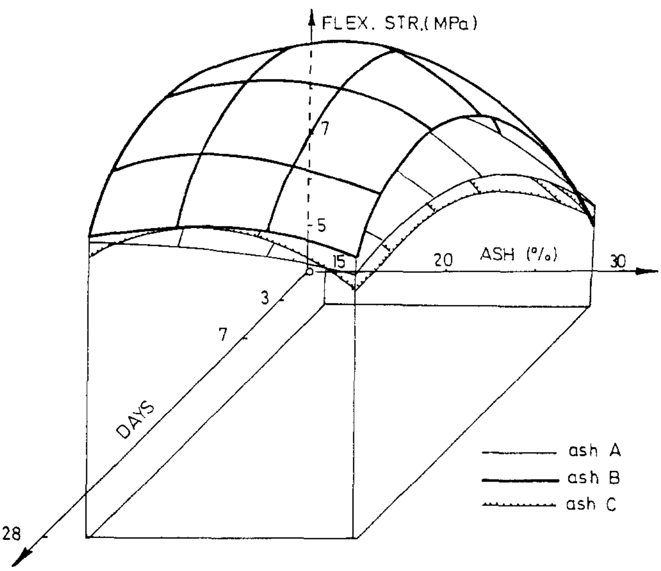
Fig.11. Maximums of Both Strengths Versus Ash Quantity

-minimal amount of ash (up to 15 wt%), added to the pure cement, decreases its mechanical characteristics,

-further increase of ash quantity (from 15 wt% to 20 wt%) causes a raising of both strengths. But, if the increase of ash amount continues towards maximum (30 wt%) all mechanical characteristics, in all periods of time, start to decrease. Only few t- factors show insignificant differences in strengths among the samples with various ash quantities (particularly for ash A),

-all findings are valid for the studied period of time; for later (>28 days) strengths other characteristics may apply,

-it is difficult to conclude (by applying statistical methods) whether the differences among strengths of samples, with various types of ashes, can be regarded as significant . Namely , 6x9 =54 t- factors were calculated and



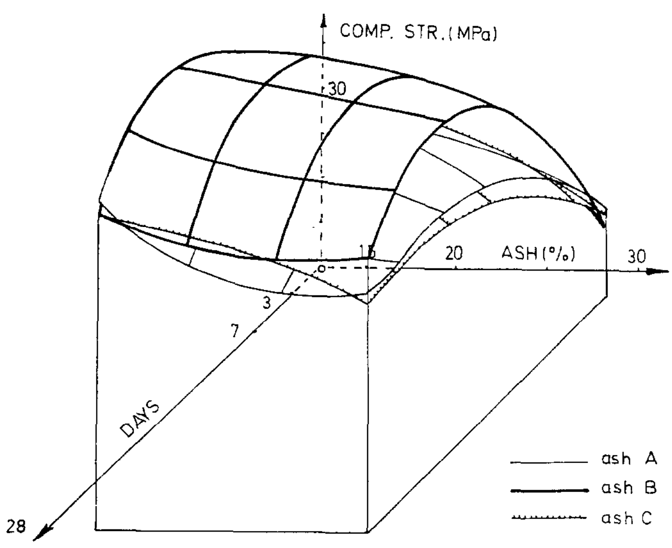


Fig.12. Comparison of Response Surfaces

24 t- factors (allmost one half) declare that the samples do not differ significantly.

However, other mathematical method (the Regression Analysis) enables deriving of mathematical models which define flexural (compressive) strength not only as a function of applied ash quantity but also as a function of period of curing time. Adequate response surfaces , shown in Figs. 7 - 10, are obviously unimodal and all have maximums (optimums) as presented in Table 3 and Figs. 7 - 10. These (absolute) optimums are far too above the standard values and can be relaxed by increasing ash quantity , up to the maximal amount (30 wt%).

As far as different types of ashes are concerned , a comparison is presented in Fig.12. Obviously, a slight advantage can be given the ash B.

Finally , it can be concluded that the suggested modification of known optimization methods successfully solves the problem of finding optimal mixture recipe (with ash as a component), from the point of view of minimization of energy cost and maximization of mechanical properties of product.

Nomenclature

b	Coefficient of a mathematical model
F	Modified objective function
g	Restriction
y	Particular mechanical characteristic
x_1, x_2	Feasible variables (ash quantity and curing time)
x_3, x_4	Artificial variables
σ	Error among measured and calculated values

References

[1] Bhatty, J.I., Marijnissen, J., Reid, K.J., Portland Cement Production Using Mineral Wastes, Cement Cocrete Res., Vol. 15, p 501 (1985)

[2] Valenti, G.L., Cioffi, R., Sersale, S., Behaviour of Italian Fly Ash in Portland Cement Mortars, Proc. 8-th Int.Congr.on the Chemistry of Cements, Vol. IV, Th.3, p 228, Rio de Janeiro, Brazil (1986)

[3] Mehta, P.K., Gjorv, O.E., Properties of Portland Cement Containing Fly Ash and Condensed Silica- Fume, Cement Concrete Res., Vol.12, p 587 (1982)

[4] Majling, J., Della M.R., The Potential of Fly Ash for Cement Manufacture, Am.Ceram.Soc.Bull., Vol. 72, No 10, (1993)

[5] Dragicevic, Lj., Rsumovic, M., Prognosis of Characteristics of Multicomponent Materials on Example of Flexural Strength of Portland Cement, Cement Concrete Res., Vol. 42, p 47 (1988)

[6] Djuric, M., Ranogajec, J., Marinkovic-Neducin, R., Petrasinovic Stojkanovic, Lj., Calculation of Optimal Mixtures, Interceram, Vol. 38, p 15 (1989)

[7] Petrasinovic-Stojkanovic, Lj., Djuric, M., Predicting a Compressive Strength of Portland Cement and Optimizing Its Raw Mixture Composition, Cement Concrete Res., Vol. 20, p 484, (1990)

[8] Djuric, M., Petrasinovic-Stojkanovic Lj., Quasi Multigoal- Programming Method Applied to the Raw Mixtures, Interceram, Vol. 40, p 213 (1991)

[9] Fisang, Lj., Ranogajec, J., Marinkovic-Neducin, R., Djuric, M., Investigation of Fly Ash as a Secondary Raw Material in Cement Industry, Proc.2-nd Int.Symp.on Environment.Contam. in Central and Eastern Europe, Budapest, Hungary (1994)

[10] Yugoslav Standard JUS B.C1.011, p 6 (Table 4) (1982)