INTERNATIONAL JOURNAL OF CIVIL AND STRUCTURAL ENGINEERING
Volume 1, No 3, 2010

Research article ISSN 0976 – 4399

Determination of Modulus of Rupture of Pavement Concrete with Silica Fume and Fly Ash using Taguchi Technique

Osman Unsal Bayrak[1], Fatih Hattatoglu , Sinan Hinislioglu[1]

1- Ataturk University, Department of Civil Engineering, Erzurum, Turkey
2- Ataturk University, Erzurum Vocational of High School , Erzurum, Turkey
fhattat@atauni.edu.tr

ABSTRACT

The purpose of this study is to optimize the 28 days modulus of rupture of concrete pavement (CP) by using the Taguchi Method. The experiments were designed using an orthogonal array technique in L_{16} array with four factors, namely, the water/cementitious ratio of 0.30, 0.35, 0.40 and 0.45, four different types of gradations with maximum aggregate size of 32 mm, 0, 5, 10, 15% Fly ash and 0, 10, 20 and 30% Silica fume by weight of cement. The signal to noise ratio (S/N) were calculated for evaluating the experimental results then the S/N values were analyzed using an analysis of variance (ANOVA) technique. According to the ANOVA results, water/cementitious ratio play significant role for modulus of rupture of CP. Moreover, the optimum conditions were found to be 0.30 water/cementitious ratio, type IV gradation containing 33% from 16-32 mm sieve, 20% from 8-16 mm, 17% from 4-8 mm and 30% from 0-4 mm aggregate, 10% FA content and 20% SF content for 28 days modulus of rupture. The modulus of rupture of 6.70MPa was obtained at the optimum conditions.

Keywords: Pavement Concrete; Silica Fume; Fly Ash; Flexural Strength; Taguchi Method

1. Introduction

In recent years, high strength concrete has increasingly been used in transportation engineering work because it has an advantage of increasing mechanical properties. The premature deterioration of pavement concrete structures under loading has led to the development of high performance concrete. It is required that pavement concrete must have high strength properties because it is subjected to destructive traffic loads. Generally high strength concrete is achieved by using superplasticizer to reduce the water-binder ratio and by using supplementary cementing materials such as silica fume or fly ash in order to create extra strength by puzzolanic reaction. It was found that the combination of two can be used in producing high strength concrete (Jaturapitakkul et al., 2003). Mineral admixtures, such as silica fume and fly ash, provide additional reaction to the porosity of the mortar matrix and improve the interface with the aggregate (Hassan et al., 2000). Fly ash is a by-product of coal-burning power plants. It is widely used as a cementitious material and a puzzolanic ingredient in concrete. The use of fly ash in concrete is constantly increasing because it improves the properties of concrete, namely workability, durability and strength in concrete (Jaturapitakkul et al., 2003). However, the strength development of fly ash concrete is relatively slower at early age (Bajorski and Streeter, 2000: Yasar et al., 2003) because the puzzolanic reaction is too slow to start and it does not progress to any significant degree until several weeks after the start of hydration (Berry, 1980). Silica fume (SF) is also a promising admixture for pavement concrete (Anonymous, 1996: Zemajits et al., 1998: Pinto and Hover, 1997: Whiting and Detwiler, 1998). It is a powder by-product resulting from the manufacture or ferrosilicon and silicon metal. It has a high content of glassy of silicon dioxide (SiO_2) and

Research article ISSN 0976 – 4399

consists of very small spherical particles. That is why it has been a popular mineral admixture to use in high strength concrete. However, silica fume is expensive compared to Portland cement type I or fly ash (Hassan et al., 2000). It is well known that silica fume is mostly made up of free silica and has a large specific surface, so it is very active in reacting with the hydrates of cementing (Jianyong and Pei, 1997). It appears to be a potential solution to overcome the negative effect of FA on the early age properties of FA – cement mixtures. Because, when SF is incorporated, the hydration rate of cement increases at early hours. The increased rate of hydration may be attributable to the ability of silica fume to provide nucleating sites to precipitating hydration products like lime, C–S–H, and ettringite. The formation of dense C–S–H gel and more homogeneous product at the interfacial zone leads to rapid strength development at early ages (Yi and Feldman, 1985).

Aggregate type influences the performance of concrete and the pavement in which it is used. Although standard specifications frequently mention the proportions of coarse and fine aggregate, the exact proportions are developed by laboratory tests to establish the most economical combination of the available fine and coarse aggregate that will produce concrete of the required strength. The ratio of water to cementitious material has so powerful an effect on the strength of the concrete, however that more attention is paid to water/cementitious (w/c) ratio than to grading of the mineral aggregate. Therefore, it should be taken both factors into account and, determined the proportion of coarse and fine aggregate of the kinds available that will produce concrete of the desired strength at the lowest cost.

Because of bending forces to which pavement concrete are subjected on road, due to the action of load and environmental conditions, modulus of rupture (MR) is one of the most important mechanical properties of pavement concrete. For 28 days curing, many specifications require different MR values such as 3,5 to 5 MPa. The objective of this study was to determine the optimum amount of fly ash and silica fume, type of gradation and w/c ratio in the pavement concrete providing the specification limit for 28 days MR using Taguchi Method. This method was explained in Section 2.3.

2. Materials and Methods

2.1. Materials

ASTM Type I, Portland cement (PC), from Set cement factory in Ankara, Turkey, was used in this study. SF, FA, superplasticiser, limestone and natural sand were obtained from Antalya Electro Metallurgy Enterprise, Çayırhan Thermal Power Plant, Aşkale and Serçeme River in Erzurum in Turkey, respectively. The chemical composition and physical properties of PC, FA and SF used in this study are summarized in Table 1.

ASTM Type I PC was added as the basic cementitious material. The dosage was 350 kg/m^3. SF and FA were added as a partial replacement of the cement at levels of 0%, 10%, 20%, and 30% based on the some previous studies (Shannag, 2000: Demirboğa, 2003: Duval and <kadri, 1998) and 0%, 5%, 10% and 15% by weight of the total cementitious materials, respectively. The water/cementitious (w/c) ratios were 0.30, 0.35, 0.40 and 0.45. The superplasticiser was slightly adjusted for some mixes to maintain approximately the same workability.

Research article ISSN 0976 – 4399

Table 1: Chemical analysis and physical properties of PC, SF and FA

Component	PC (%)	SF (%)	FA (%)
SiO_2	19.80	88.95	47.5
Fe_2O_3	3.42	0.5 – 1	16.3
Al_2O_3	5.61	1 – 3	15.95
CaO	62.97	0.8 – 1.2	6.6
MgO	1.76	1.0 – 2.0	4.65
SO_3	2.95	–	–
K_2O	0.3	–	–
TiO_2	0.2	–	–
Sulphide (S^{2-})	0.17	0.1–0.3	–
Chloride (Cl^-)	0.04	–	–
Undetermined	0.30	–	–
Free CaO	0.71	–	11.5
LOI	0.36	0.5–1.0	2.4
Specific gravity	3.15	2.18	2.4
Specific surface (cm^2/g)	3410	–	–
Remainder on 200-mm sieve (%)	0.1	–	–
Remainder on 90-mm sieve (%)	3.1	–	–
Compressive strength (MPa)			
2 days,	24.5	–	–
7 days	42.0	–	–
28 days	44.4	–	–

Table 2: Gradations used in the study (percent retained)

Sieve sizes (mm)	Type of Gradation			
	I	II	III	IV
16 – 32	38	20	27	33
8 – 16	24	18	19	20
4 – 8	15	15	16	17
0 – 4	23	47	38	30

The coarse aggregate was crushed limestone with maximum size of 32 mm and natural sand with a fineness modulus of 2.66 was used for making concrete mixtures. The four different types of gradations used in this study are shown in Table 2. For each mix, two 100*100*400 mm beams were cast. The beams were demoulded after 24 hours and stored in a lime saturated water tank at 21 ± 1^{o}C until tested at 28 days. Two beams of each mix were cast. MR values of each beam were determined accordance with ASTM C78.

Research article ISSN 0976 – 4399

2.2. Experimentation approach

In the traditional approach of experimentation, while one factor is kept varying, all the other factors are kept constant. If the interactions between the factors are present, the optimum conditions obtained from the conventional approach may not be a true optimum. The number of experiments is numerous for full factorial design, and it is practically not possible to carry out the experiments in most of the cases. To reduce the number of experiments in a research study, several experimental design have been suggested (Roy, 1990). Among several experimental design techniques, the Taguchi method has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters (Roy, 1990: Kackar, 1985: Phadke, 1989: Kim et al., 2003: Yang and Tarng, 1998: Hınıslıoglu and Bayrak, 2004). One of the advantageous of Taguchi method over the conventional experiment design methods, in addition to keeping the experimental cost at the minimum level, is that minimizes the variability around the target when bringing the performance value to the target value. Another advantage is that optimum working conditions determined from the laboratory work can also be reproduced in the real production environment. Basically the Taguchi method is a powerful tool for design of quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality and cost (Kackar, 1985).

Therefore the fractional factorial experiments using orthogonal array was investigated by Taguchi variation (Roy, 1990: Kackar, 1985), which can substantially decrease the number of experiments. The linear graph developed by Taguchi (1962) is useful to scientists and engineers to design and analyze the experimental data without having basic knowledge of factorial design.

2.3. Taguchi Analytical Methodology

The Taguchi method is a powerful tool for the design of a high quality system. It provides a systematic approach to optimize designs for performance and quality. Further, Taguchi parameter design can optimize the performance through the settings of design parameters and reduce the sensitivity of system performance to sources of variation (Roy, 1990: Kackar, 1985).

The use of quantity design in the Taguchi method to optimize a process with one or multiple performance characteristic includes the following steps:

1- to identify the performance characteristic and select process quantities (factors) to be evaluated; 2- to determine the number of quantity levels for the process and possible interaction between the process quantities (factors); 3- to select the appropriate orthogonal array and assignment of the process quantities (factors) to the orthogonal array; 4- to conduct the experiments based on the arrangement of the orthogonal array; 5- calculate the performance statistic; 6- to analyze the experimental result using the performance characteristic and ANOVA; 7- to select the optimal levels of process quantities (factors); 8- to verify the optimal process quantities (factors) through the confirmation experiment (Roy, 1990).

Research article ISSN 0976 – 4399

The performance characteristic was chosen as the optimization criteria. There are three categories of performance characteristics, the larger-the better, the smaller-the better and the nominal-the better. These performance characteristics are evaluated by using Eq 1-3.

The larger the better $$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \quad (1)$$

The smaller the better $$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right) \quad (2)$$

The nominal the better $$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_0)^2\right) \quad (3)$$

where S/N (S/N unit: dB) are performance statistics, defined as the signal to noise ratio, n the number of repetitions for an experimental combination, and Y_i a performance value of the i_{th} experiment and Y_o nominal value desired.

2.4. Orthogonal Array

The experiments were designed based on the orthogonal array technique. Factors and their levels affecting the early MR of concrete pavement were decided based on the brainstorming session and literature review on the subject. Four factors and four levels of each factor have been taken for experimentation (Table 3). In the orthogonal array technique, the minimum required experiments for four factors at four levels are 16. It is therefore designed in $L_{16}(4^5)$ (Table 4). The order of the experiments was obtained by inserting parameters into columns of the orthogonal array, L_{16} (4^5), chosen from the experimental plans given in Table 4. But the order of experiments was randomly made to avoid noise sources which had not been considered initially and which could take place during an experiment and affect the results in a negative way.

Table 3: Parameters and their values corresponding to their levels to be studied

Factors	**Levels**			
	1	2	3	4
A (water/cementitious ratio)	0.30	0.35	0.40	0.45
B (gradation type)	I	II	III	IV
C (fly ash content) (%)	0	5	10	15
D (silica fume content) (%)	0	10	20	30

Research article ISSN 0976 – 4399

Table 4: Orthogonal Array for $L_{16}(4^5)$

Experiment number	Columns							
	A (w/b)	B (grad)	C (FA)	D (SF)	Error column	Test Results (MPa)		Performance Statistics (S/N)
1	1	1	1	1	1	4.7	5.52	14.084
2	1	2	2	2	2	5.72	6.37	15.90
3	1	3	3	3	3	6.59	7.28	16.788
4	1	4	4	4	4	6.44	6.25	16.045
5	2	1	2	3	4	6.74	6.16	16.164
6	2	2	1	4	3	5.83	5.5	15.052
7	2	3	4	1	2	4.98	5.36	14.252
8	2	4	3	2	1	6.3	5.78	15.596
9	3	1	3	4	2	4.62	4.31	12.980
10	3	2	4	3	1	4.42	4.31	12.797
11	3	3	1	2	4	4.72	4.87	13.612
12	3	4	2	1	3	4.96	5.1	14.028
13	4	1	4	2	3	4.53	4.94	13.481
14	4	2	3	1	4	4.65	4.92	13.587
15	4	3	2	4	1	4.38	4.22	12.664
16	4	4	1	3	2	4.47	4.62	13.147
						Average		14.367

2.5 Procedure for Taguchi Method

In the optimization, two samples were prepared for each mix. S/N values were calculated based on the quality characteristic of “the bigger the better” using Eq. (1). The levels of parameters that maximize the S/N were optimum. However, in the Taguchi Method the experiment corresponding to optimum working conditions might not have been performed during experiments. In such cases the performance value corresponding to optimum working conditions can be predicted by utilizing the balanced characteristic of the orthogonal array using Eq. (4) (Roy, 1990):

$$Y_i = \mu + X_i + e_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where μ is the overall mean of performance value, X_i the fixed effect of the parameter level combination used in *ith* experiment, and e_i the random error in *ith* experiment. Because Eq. (4) is a point estimation, which is calculated by using experimental data in order to

Research article ISSN 0976 – 4399

determine whether results of the confirmation experiments are meaningful or not, the confidence interval must be evaluated. The confidence interval at a chosen error level may be calculated by Eq.(5):

$$CI = \mu \pm \sqrt{F(1, n_2) x V_e / N_e} \quad (5)$$

Where

μ = average expected performance statistic at the optimum conditions

$F(1,n_2)$ = F value from the F Table from any statistical book at the required confidence level and at DOF 1 and error DOF n_2

V_e = Variance of error term (from ANOVA)

N_e = Effective number of replications

$$N_e = \frac{Total\ number\ of\ results(or\ number\ of\ S/N\ ratios)}{DOF\ of\ mean(=1\ always) + DOF\ of\ all\ factors\ included\ in\ the\ estimate\ of\ the\ mean}$$

3. Results and Discussion

S/N (signal to noise) ratios corresponding to the measured MR values are given in Table 4 (Bayrak, 2002). Since the bigger-the better is selected as performance statistics, Eq.1 is used to calculate the S/N values in Table 4. This S/N calculation procedure can be explained with an example. For the first S/N data in Table 4 can be calculated as follows;

$$S/N = -10 \log_{10}(1/2(1/4.7)^2 + (1/5.52)^2)$$

$$S/N = 14.084$$

The other S/N values can be calculated with the same procedure.

At first sight, it is difficult and complicated to follow experimental conditions for the graphs given in the figure 1. The procedures can be explained with an example. Figure 1 shows the variation of the performance statistics (S/N) with parameters on the MR. Now, let us try to determine the experimental conditions for the first data point for the effect of SF content on the S/N. The SF content for this point is 0%, which is the level 1 for this parameter. The experiments corresponding to the SF content level 1 are found from the Table 4 (Column D). It is seen in Table 4 that the experiments for which the Column D is 1 are experiments with experiment numbers 1,7,12, and 14. The performance statistics value of the first data point is, thus, the average of those obtained from the experiments with experiment numbers 1,7,12 and 14. ((14.084+14.252+14.028+13.587)/4 = 13.988) The experimental conditions for the second data point, thus, are the conditions of the experiments for which column D is 2 (i.e., experiments with experiment numbers 2, 8, 11 and 13.) and so on. All the data points calculated according to the above procedure are given in Table 5. Average effects of each level for the various factors are given in Table 5 and shown in Figure 1.

INTERNATIONAL JOURNAL OF CIVIL AND STRUCTURAL ENGINEERING
Volume 1, No 3, 2010

Research article ISSN 0976 – 4399

Figure 1: The effects of w/c ratio, type of gradation, fly ash content and silica fume content on S/N ratio.

Table 5: The average S/N effects

Level Number	Factor A	Factor B	Factor C	Factor D
1. Level	15,627	14,177	13,974	13,988
2. Level	15,266	14,257	14,612	14,570
3. Level	13,354	14,329	14,738	14,724
4. Level	13,220	14,707	14,144	14,186

3.1. Evaluation of Analysis of Variance (ANOVA)

3.1.1 Analysis of variance (ANOVA) before pooling

The analysis of variance computes quantities known as degrees of freedom, sums of squares etc. and organizes them in a standard tabular format. ANOVA establishes the relative significance of the individual factors. These quantities in Table 6 are defined as shown below. The steps are as follows.

Step1. Total of all results:

T=14.084 + 15.59 + 16.788 +………………………+ 13.147 = 229.88

Step 2. Correction factor:

$CF=T^2/n=229.88^2/16=3302.70$

n: Total number of experiments

Step 3. Total sum of squares:

Research article ISSN 0976 – 4399

$$S_T = \sum_{i=1}^{16} y_i^2 - CF$$

S_T=(14.084^2+15.59^2+……….13.147^2)-3302.70

S_T=26.33

Step 4.

Factor sum of squares:

$$S_A = A_1^2 / N_{A1} + A_2^2 / N_{A2} + A_3^2 / N_{A3} + A_4^2 / N_{A4} - CF$$

$A_1 = A_{11}+A_{12}+A_{13}+A_{14}$=14.084+15.59+16.789+16.046=62.51

$A_2 = A_{21}+A_{22}+A_{23}+A_{24}$=16.165+15.053+14.252+15.597=61.07

$N_{A1} = 4$ (Total number of experiments in which factor A_1 is present)

$N_{A2} = 4$ (Total number of experiments in which factor A_2 is present) and so on

$$S_A = \frac{1}{4}\sum_{i}^{4} A_i^2 \text{ - CF}$$

S_A = 62.51^2/4 +61.07^2/4+………-3302.7

S_A = 18.947

Step 5. Total and Factor Degrees of Freedom (DOF)

DOF total = Number of test runs minus 1

or f_A = n-1 = 4-1 = 3 and so on.

$$S_e = S_T - \sum SS\ of\ all\ factors$$

S_e = 26.33 – (18.947 + 0.652 +1.607 + 1.381)

S_e = 3.742

Step 6. Mean Square (Variance):

The variance of each factor is determined by the sum of square of each trial sum result involving the factor, divided by the degrees of freedom of the factor. Thus:

$V_a = S_a/f_a$ = 18.947/3 = 6.315

and so on.

Step 7. Pure sum of squares

$S'_a = S_a-(V_e \times f_a)$

S'_a = 18.947-(1.247x3)

S'_a = 15.204

Step 8. Percentage Contribution:

Research article ISSN 0976 – 4399

$P_a = S'_a/S_T = 15.204/26.33$

$P_a = 0.57743$

Table 6: ANOVA Table before pooling

Source	DOF	Sums of Squares	Variance	F-Ratio	Pure Sum	Percent (P)
Factor A	3	18,947	6,315	5,062	15,204	57,743
Factor B	3	0,652	0,217	0,174	0	0
Factor C	3	1,607	0,353	0,429	0	0
Factor D	3	1,381	0,460	0,369	0	0
Other/Error	3	3,742	1,247			42,257
Total	15	26,331				100

According to the ANOVA before pooling, it is seen that only w/c ratio affect the MR of the pavement concrete. The other three factors have no influence on the MR statistically. This means that any levels of these factors can be used in a pavement concrete mix design. However, it is well known that if the effect of factor/factors on the dependent variable is very small, these factors should be pooled to obtain lower error variance. Therefore, fly ash and silica fume content and type of gradation are pooled.

3.2 Procedure for pooling

When the contribution of a factor is small, as for factor B, C and D (type of gradation, fly ash content and silica fume content) in this study, the sum of squares for these factors are combined with the error S_e. This process of disregarding the contribution of the selected factor and subsequently adjusting the contributions of the other factors is known as pooling. Sum of squares of factors B, C and D are added to the sum of squares of error. Then, the contribution of the remaining factors to the S/N is recalculated. The ANOVA Table after pooling was given in Table 7.

Table 7: ANOVA Table after pooling

Source	Pool	DOF	Sums of Squares	Variance	F-Ratio	Pure Sum	Percent (P)
Factor A	N	3	18,947	6,315	10.263	17.10	64.95
Factor B	Y	(3)	(0,652)				
Factor C	Y	(3)	(1,607)				
Factor D	Y	(3)	(1,381)				
Other/Error		12	7.383	0.615	10.263	17.101	35.05
Total		15	26,331				100

Research article ISSN 0976 – 4399

Analysis of variance (ANOVA) after pooling

ANOVA after pooling begins from step 5.
SS_{error} = 3.47 + 0.652 + 1.607 + 1.381
SS_{error} = 7.383
After pooling, DOF of the error term is 12.
$V_{error} = SS_{error} / DOF_{error}$
Verror = 7.383/12 = 0.615
Pure sum of square
$S'_a = S_a-(V_e \times f_a)$
S'_a = 18.947 – (0.615*3)
S'_a = 17.102
Percent contribution
P_a = 17.102/26.33
P_a = 0.6495

3.2. Calculation of the expected performance (EP) at the optimum conditions

The optimum condition for the bigger the better is A_1 B_4 C_3 D_3. The average S/N values for each factor are given in Table 5. The graphs in Figure 1 are drawn according to these values in Table 5. Although only factor A is considered as significant factor according to the ANOVA Table after pooling, the performance at the optimum condition is estimated using all factors. The numerical value of the maximum point in each graph marks the best value of that particular parameter. The maximum values for each parameter are given in Table 8. In addition, if the experimental plan given in Table 4 is studied carefully, it can be seen that an experiment corresponding to the optimum conditions A_1 B_4 C_3 D_3 was not performed during the experimental work. Thus, it should be noted that MR value of 16.691 given in Table 8 is the predicted result by using equation 4. 16.691 is average of performance from the Table 4. Expected Performance is calculated using both the average S/N value and the S/N values for A_1, B_4, C_3, and D_3 in Table 5.

EP = 14.367 + (15.627-14.367) + (14.707 – 14.367) + (14.738 – 14.367) + (14.724 – 14.367)
EP = 16.691

In order to test this expected result, confirmation experiments were conducted twice at the predicted optimum working conditions. Modulus of rupture of 6.70 and 6.85 MPa with 6.78 MPa as the average were obtained from the confirmation experiments at the same experimental conditions as in Table 8.

3.3. Confidence Interval (CI) of Factor Effect

The confidence interval of prediction at the 95% significance level is given as 14.501 – 18.88 in Table 8 as predicted from equation 5. CI was calculated as follows.

n_2 = 3 (Since the estimation includes all the factors, this value is taken from the ANOVA Table before pooling, Table 6)
N_e = 16/(1+12) = 1.23
F(1,3) = 4.75 (From the F Table at the level of significance 0.05)

Research article ISSN 0976 – 4399

$V_e = 1.2475$

$CI = 16.691 \pm \sqrt{4.75x1.2475/1.23}$

$CI = 16.691 \pm 2.19$

The confirmation test result showed that two replications are well within the calculated confidence interval. It can be said that the experimental results are within 95% confidence level. These results show that the interactive effects of the factors are negligible for early MR of concrete and also that the Taguchi Method can successfully be applied to the early MR experiments, with a limited number of experiment and in a shorter time.

Table 8: Optimum conditions maximizing 28 days modulus of rupture and prediction of performance

Factors	Level No	Contribution to the S/N
A	1	1.259
B	4	0.337
C	3	0.371
D	3	0.357
Total contribution of all factors (S/N)		2.323
Average performance statistic (S/N)		14.367
The expected value in optimum conditions (S/N)		16.691
Confidence interval (Confidence level α=95%) (S/N)		14.501 – 18.88
Confirmation test result (S/N)		16.81
Confirmation test result (MPa)		6.93

3.4. Evaluation of factor effects

3.4.1 Effect of water/binder ratio

The effect of w/b ratio on the MR of concrete pavement is shown in Fig. 1. According to ANOVA, water content affects significantly on the properties of concrete (Table 6). It has been known that compressive strength varies inversely with the w/c ratio for concrete (Rao, 2001). In another word, while w/c ratio decrease strength of concrete increase. From the test results, first level of w/c ratio (0.30) maximizes the S/N as it is expected.

3.4.2 Effect of gradation type

It is seen that although all the gradations have nearly same effect on the MR of concrete pavement, maximum MR was achieved from the type IV gradation.

3.4.3 Effect of fly ash

The effect of FA on MR is given in Figure 1. Test results showed that all levels of FA replacement increased MR when compared with control concrete. However, after 10% replacement of FA the strength development decreases a little. In the optimum conditions,

Research article ISSN 0976 – 4399

mix with 10% FA content maximized the MR. These observations are consistent with the results of other studies (Naik et al., 1996). It is known that mineral admixtures such as FA act as pozzolanic materials as well as fine filler, therefore the microstructure of hardened cement matrix becomes denser and stronger (Bharatkumar et al., 2001). In addition increase in MR may be due to the large pozzolanic reaction and improved interfacial bond between paste and aggregates (Siddique, 2003). Moreover, fly ash particles are spherical in shape; in comparison, sand particles are irregular in shape. The use of fly ash may therefore produce optimum packing conditions for the different aspect ratios of sand and fly ash during casting, thus resulting in a more homogeneous and compact final PC product (Rebeiz and Craft, 2002).

3.4.4 Effect of silica fume

The effect of SF on MR is also demonstrated in Fig. 1. It is clear from Fig. 1 that all levels of SF replacement (10%, 20% and 30%) increased the MR. Moreover, 20% SF replacement maximized the S/N at the optimum conditions. Nevertheless, MR was increased as FA content increase. However, after 20% replacement, increase in flexural strength decreased. It is known that some pozzolanic materials such as silica fume can strengthen the interfaces when used in concrete (Bentur and Kohen, 1987: Pope, 1992: Goldman and Bentur, 1989). According to the results of some studies (Wu and Zhou, 1988: Mitsui et al., 1994), addition of silica fume increased the interfacial bond strength and interfacial fracture energy by about 100%. The interfacial bond improvement effect of such materials is due to their small particle size and pozzolanic reactivity, leading to denser microstructures and stronger interfacial bond (Wong et al., 1999).

4. Conclusions

The following conclusions are made, based on the test results and on the discussion presented in this study:

1. According to ANOVA table, the significant parameter affecting the modulus of rupture is the w/c ratio.
2. The factor levels used in this study for type of gradation, FA content and SF content do not have statistically significant importance. This means that any level of these three factors can be used. However, the optimum conditions were found to be 0.30 water/cementitious ratio, type IV gradation containing 33% from 16-32 mm, 20% from 8-16 mm, 17% from 4-8 mm and 30% from 0-4 mm, 10% FA content and 20% SF content for 7 days modulus of rupture.
3. The modulus of rupture of 6.70MPa was obtained at the optimum conditions.
4. More economic mix will be obtained by using 10% FA and 20% SF instead of cement.
5. Specification requirements for the modulus of rupture desired for 28 days curing, period, 3.5 or 5 MPa, can be obtained from those at 28 days curing. This means that the pavement will open to traffic earlier.
6. In addition, it is shown that Taguchi method can be used in a pavement concrete mix design as an alternative to the more expensive conventional design of experiment methods.

Research article ISSN 0976 – 4399

5. References

1. Anonymous, 1996, Research Pays Off: New York puts industrial by-products back to work, Transportation Research Board, 50.

2. Bajorski P. and Streeter D.A., 2000, Optimization of amount and bleeding of cementitious materials in high performance concrete, Transportation Research Board, 30

3. Bayrak O.U., 2002, Optimization of the some mechanical properties of concrete pavement mix containing fly ash and silica fume by Taguchi method. MS Thesis. Atatürk University, Graduate School of Natural and Applied Science.

4. Bentur A., Cohen M.D., 1987, Effect of condensed silica fume on the microstructure of the interfacial zone in portland cement mortars, J Am Ceram Soc, 70,pp 738–743.

5. Berry E. E., 1980, Strength development of some blended-cement mortars, Cement and Concrete Research, 10,pp 1 – 11.

6. Bharatkumar B.H., Narayanan R., Raghuprasad B.K., Ramachandramurthy D.S., 2001, Mix proportioning of high performance concrete, Cement and Concrete Composites, 23,pp 71–80.

7. Demirboğa R., 2003, Influence of mineral admixture on thermal conductivity and compressive strength of mortar, Cement and Concrete Research, 35,pp 189 – 198.

8. Duval R., Kadri E. H., 1998, Influence of silica fume on the workability and the compressive strength of high-performance concrete, Cement and Concrete Research, 28,pp 533 – 547.

9. Goldman A., Bentur A., 1989, Bond effects in high-strength silica fume concrete, ACI Materials Journal, 86,pp 440–447.

10. Hassan K.E., Cabrera J.G., Maliehe R.S., 2000, The effect of mineral admixtures on the properties of high performance concrete, Cement&Concrete Composites, 22,pp 267-271

11. Hınıslıoglu S. and Bayrak O.Ü, 2004, Optimization of early flexural strength of pavement concrete with silica fume and fly ash by Taguchi Method, Civil Engineering and Environmental Systems, 1029-0249, Volume 21, Issue 2,pp 79 – 90

12. Jaturapitakkul C., Kiattikomol K., Sata V., Leekeeratikul T., 2003,Use of ground coarse fly ash as a replacement of condensed silica fume in producing high-strength concrete, Cement and Concrete Research, pp 2388.

13. Jianyong L., Pei T., 1997, Effect of slag and silica fume on mechanical properties of high strength concrete, Cement and Concrete Research, 27,pp 833-837

14. Kackar R. N. 1985,Off-line quality control parameter desing and the Taguchi method , J.Quality Technology , 17,pp 176-188

Research article ISSN 0976 – 4399

15. Kim S. J., Kim K.S. 2003, Jang H..Optimization of manufacturing parameters for brake lining using Taguchi method ,Journall of Metarials Processing Technology,136, pp 202-208

16. Mitsui K., Li Z., Lange D.A., Shah S.P., 1994, Relationship between microstructure and mechanical properties of the paste-interface, ACI Materials J, 91,pp 30–39.

17. Naik T.R., Singh S.S., Hossain M.M., 1996, Enhancement in mechanical properties of concrete due to blended ash, Cement and Concrete Research, 26,pp 45 – 54.

18. Phadke, M. S., 1989Quality Engineering using robust design,NJ: Prentice Hall, 334

19. Pinto R.C.A., Hover K. C, 1997, Effect of silica fume and superplasticiser addition on setting behavior of high-strength mixtures, Transportation Research Board, 56.

20. Pope W.A., Jennings M.H., 1992, The influence of mixing on the microstructure of the cement paste/aggregate interfacial zone and on the strength of mortar, J Mat Sci, 27,pp 6452 – 6462.

21. Rao G. A., 2001, Generalization of Abrams' law for cement mortars, Cement and Concrete Research, 31,pp 495 – 502.

22. Rebeiz K. S., Craft A. P., 2002, Polymer Concrete Using Coal Fly Ash, Journal of Energy Engineering, 128,pp 62 – 73.

23. Roy, R. K., 1990, A Primer on the Taguchi Method, Competitive Manufacturing Series.

24. Shannag M. J., 2000, High strength concrete containing natural pozzolan and silica fume, Cement and Concrete Research, 22 ,pp 399 – 406.

25. Siddique R., 2003, Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete, Cement and Concrete Research, 33,pp 539 – 547.

26. Taguchi G., 1962, Tables for orthogonal arrays and lineer graphs, Maruzen. Tokyo.

27. Whiting D., Detwiler R., 1998, Silica fume concrete for bridge decks, Transportation Research Board,1.

28. Wong Y.L., Lam L., Poon C.S., Zhou F.P., 1999, Properties of fly ash-modified cement mortar-aggregate interfaces, Cement and Concrete Research, 29,pp 1905–1913.

29. Wu K., Zhou J., 1988, The influence of the matrix-aggregate bond on the strength and brittleness of concrete, in: Bonding in Cementitious Composites, Symposium proceedings, vol. 114, Materials Research Society, Pittsburgh, pp 29–34.

30. Yang W.H., Tarng Y.S., 1998, Desing optimization of cutting parameters for turning operations based on the Taguchi method , Journall of metarials processing Technology, 84,pp 122-129

Research article ISSN 0976 – 4399

31. Yasar E., Atis C. D., Kilic A., Gulsen H., 2003,Strength properties of lightweight concrete made with basaltic pumice and fly ash, Materials Letters, (), 57, pp 2267 – 2270.

32. Yi H.C., Feldman R. F., 1985, Hydration reactions in Portland cement-silica fumeblends, Cement and Concrete Research, 15,pp 585 – 592.

33. Zemajits J., Weyers R.E., Sprinkel M. M., 1998, Corrosion protection service life of low-permeable concretes and low-permeable concrete with a corrosion inhibitor, Transportation Research Board, 51.