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INVESTIGATION OF COMPRESSIVE STRENGTH OF PAVEMENT CONCRETE BY THE TAGUCHI METHOD

YOL BETONLARININ BASINÇ MUKAVEMETLERİNİN TAGUCHI METODUYLA ARAŞTIRILMASI

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ABSTRACT

In this study, the Taguchi method, a powerful tool to design optimization for quality, is used to determine the optimal conditions for concrete pavement with fly ash and silica fume. An orthogonal array (L_{16} with four factors with four levels each), the signal-to-noise (S/N) ratio, and the Analysis of Variance (ANOVA) are employed to investigate the compressive strength. 0.30, 0.35, 0.40 and 0.45 water/binder ratios, four different types of gradation with maximum aggregate size of 32mm, 0, 5, 10 and 15% fly ash and 0, 10, 20 and 30% silica fume replacement by weight of cement are the levels of factors. According to the results of ANOVA, water/binder ratio and type of gradation plays significant role for compressive strength of concrete pavement. In addition, the optimum conditions were found to be 0.30 water/binder ratio, Type IV gradation (70% coarse aggregate, 30% fine aggregate), 5% FA content and 10% SF content. Maximum compressive strength of 66.83 MPa was achieved at the optimum conditions.

Keywords: concrete pavement, compressive strength, fly ash, silica fume, Taguchi method

ÖZET

Bu çalışmada, uçucu kül ve silis dumanı ile üretilen yol betonlarının basınç mukavemetleri Taguchi metodu kullanılarak optimize edilmiştir. Basınç mukavemetini araştırmak için L_{16} ortogonal dizisi (her biri dört seviyeli dört faktör), sinyal/gürültü oranı (S/N) ve varyans analizi kullanılmıştır. Faktörler ve seviyeleri olarak 0.30, 0.35, 0.40 ve 0.45 su/çimento oranı, maksimum dane çapı 32 mm olan dört farklı gradasyon, çimento ağırlığının 0, 5, 10 ve 15% uçucu kül ve 0, 10, 20 ve 30% silis dumanı kullanılmıştır. ANOVA tablosuna göre, yol betonlarının basınç mukavemetleri üzerine su/çimento oranı ile gradasyon tipinin çok büyük etkisinin olduğu görülmüştür. Bununla birlikte, optimum şartlardaki faktör ve bunların seviyeleri ise 0.30 su/çimento oranı, IV tip gradasyon (70% iri agreega, 30% ince agrega), 5% uçucu kül içeriği ve 10% silis dumanı içeriği olarak bulunmuştur. Optimum şartlarda maksimum 66.83 MPa'lık basınç mukavemeti elde edilmiştir.

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Anahtar Kelimeler: Beton yollar, basınç mukavemeti, uçucu kül, silis dumanı, Taguchi methodu

INTRODUCTION

There are numerous expected properties from a modern pavement. Especially it is very important to have adequate strength against the destructive traffic loads, to be economical and to have minimum maintenance and rehabilitation costs (Ağar vd., 1998). The utilization of concrete pavement (CP) has been widely increased in the world as an alternative to the flexible pavement due to its high strength and rigidity, and minimum total cost.

In the last few decades, fly ash (FA) and silica fume (SF) have been increasingly used as mineral admixtures in concrete. Most of these materials are industrial by-products and help reducing the amount of cement required to make concrete less costly and environmental friendly. FA is commonly used pozzolonic admixture in paving concrete (Senadheera vd., 1996; Abou-Zeid vd., 1996; Zemajits vd., 1998; Bajorski ve Streeter, 2000). In recent years, the use of FA in concrete has been accepted primarily because of resulting economy through the saving cement, secondly using industrial wastes, and thirdly producing durable materials (Berry, 1980; Poon vd., 2001; Wu ve Naik, 2002; Targan vd., 2002; Yasar vd., 2003). The replacement level can be more than 50% (ACI Committee, 1998). It has been well established that concretes prepared from FA have lower permeability which results in durable concrete however the compressive strength development is slower when compared with concrete prepared from Portland Cement (PC). This is due to large particle sizes and hence reduced surface area of FA which causes it to hydrate slowly in presence of alkaline solution formed by dissolution of cement particles (Khatri vd., 1995). SF 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 (Whiting ve Detwiler, 1998). However, researchers disagree about the definition of the optimal content of silica fume, which enables us to obtain the highest strengths. To some researchers (Yogendran vd., 1987; Sautsos ve Domone,1993), the content is about 15%, whereas to others (Toutanji ve El-Korchi, 1995; Malhotra ve Carette, 1983), the increase in compressive strength may reach from 30 to 40% of replacement of cement by silica fume.

In a concrete mix design, it is well known that as the number of mix variables is increased, the number of experiments increases. In this case, more material, personal, money and time requires for traditional design of experiments. Taguchi method has been commonly used to decrease the number of experiments in such cases (Sirinivasan *et al.*, 2003). The aim of the present work is to determine the optimal conditions for concrete pavement with fly ash and silica fume. The experimental work was so designed that the experiments gave the optimum working conditions of the factors which affect the compressive strength for 28 days, using the Taguchi Method.

EXPERIMENTAL PROGRAM

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 was added as a partial replacement of the cement at levels of 0, 10, 20, and 30% based on the some previous studies (Toutanji ve El-Korchi, 1995; Malhotra and Carette, 1983), and 0, 5, 10 and 15% by weight of the total cementitious materials, respectively. The water/binder (w/b) ratios were 0.30, 0.35, 0.40 and 0.45. The dosage level of superplasticiser was slightly adjusted for some mixes to maintain approximately the same workability. 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 concrete mixtures. The four different types of gradations used in this study are shown in Table 2

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 (kg/cm^2)			
2 days,	24.5	–	–
7 days	42.0	–	–
28 days	44.4	–	–

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

Sieve sizes	Type of Gradation			
(mm)	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

Three specimens of 100 mm in diameter and 200 mm in height were cast for each mix. The specimens were demoulded after 24 hours and stored in a water tank at 21 ± 1°C until tested at 28 days.

Method

In the traditional approach of experimentation, while one factor is kept varying, all the other factors are kept constant. The optimum conditions arrived in the conventional approach may not be a true optimum if the interactions between the factors are present. To study the factors and its interactions, factorial experiments and response surface designs are available. In the case of a full factorial design, the number of experiments is large, and it is practically not possible to carry out the experiments in most of the cases. So the fractional factorial experiments using orthogonal array was investigated by Taguchi (Roy, 1990; Peace, 1993), which can substantially decrease the number of experiments and make it to study the effect of factors and its interactions. The linear graph developed by Taguchi (Roy, 1990) is useful to scientists and engineers to design and analyze the experimental data without having basic knowledge of factorial design.

Orthogonal Array

The experiments were designed based on orthogonal array technique. Factors and their levels affecting compressive strength 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. In the orthogonal array technique, the minimum required experiments for four factors at four levels are 16, so it is designed in $L_{16}(4^5)$ (Table 3).

Table 3. Factors and their values corresponding to their levels to be studied

Factors	**Levels**			
	1	**2**	**3**	**4**
A (water/binder 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

The order of the experiments was obtained by inserting factors into columns of orthogonal array, L_{16} (4^5), chosen as experimental plans given in

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 results in a negative way.

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

Experiment number	Columns					
	A (w/b)	B (grad)	C (FA)	D (SF)	Unused	Performance Statistics (S/N)
1	1	1	1	1	1	33.25
2	1	2	2	2	2	35.02
3	1	3	3	3	3	33.74
4	1	4	4	4	4	34.06
5	2	1	2	3	4	33.09
6	2	2	1	4	3	33.04
7	2	3	4	1	2	31.49
8	2	4	3	2	1	34.93
9	3	1	3	4	2	28.28
10	3	2	4	3	1	31.55
11	3	3	1	2	4	31.49
12	3	4	2	1	3	32.63
13	4	1	4	2	3	30.70
14	4	2	3	1	4	30.94
15	4	3	2	4	1	31.31
16	4	4	1	3	2	30.86
					Average	32.27

In the optimization, two samples were prepared for each mix. S/N values were calculated based on the quality characteristic of "the bigger the best" using Eq. (1):

$$S/N = -10Log\left[\frac{1}{n}\sum_{1}^{n}\frac{1}{Y_i^2}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where S/N is performance statistics, defined as the signal to noise ratio (S/N unit: dB), n number of repetition done for an experimental combination, and Yi performance value of i*th* experiment. The levels of factors that maximize the S/N were optimum. However, in Taguchi method the experiment corresponding to optimum working conditions might not have been done during the whole period of the experimental stage. In such cases the performance value corresponding to optimum working conditions can be predicted by utilizing the balanced characteristic of orthogonal array using Eq. (2):

$$Y_i = \mu + X_i + e_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where μ is the overall mean of performance value, X_i the fixed effect of the factor level combination used in i*th* experiment, and e_i the random error in i*th* experiment. Because Eq. (2) is a point estimation, which is calculated by using experimental data in order to determine whether results of the confirmation experiments are meaningful or not, the confidence interval must be evaluated. The confidence interval at chosen error level may be calculated by Eq.(3):

$$\mu \pm \sqrt{F_{\alpha;1,DF_{MSe}} MSe\left[\frac{1+m}{N} + \frac{1}{n_i}\right]} \quad \text{.....................................(3)}$$

where F the value of F table, α the error level, DF_{MSe} degrees of freedom of mean square error, m degrees of freedom used in the prediction of Yi , N the number of total experiments, and n_i the number of repetition in confirmation experiment.

RESULTS AND DISCUSSION

S/N ratios corresponding to the measured compressive strengths are given in Table 4. Average effects of each level for the factors were given in Table 5 and shown in Figure 1 (Bayrak, 2002).

Table 5. The average S/N effects

Level Number	Factor A	Factor B	Factor C	Factor D
1. Level	34.02	31.33	32.16	32.08
2. Level	33.14	32.64	33.01	33.03
3. Level	30.99	32.01	31.97	32.31
4. Level	30.96	33.12	31.50	31.67

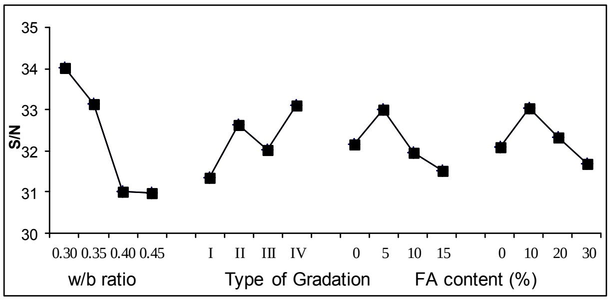

Fig. 1. The effects of the factors on performance statistics (S/N)

The primary factor that governs the compressive strength is w/b ratio as stated in (Bhanja ve Sengupta , 2002). The compressive strength of concrete varies inversely with w/b ratio. Therefore, in this study 0.30 w/b ratio maximizes the S/N as it is expected. It is seen that all the gradations have nearly same effect on the compressive strength. Maximum compressive strength was achieved from the gradation with 70% coarse aggregate and 30% fine aggregate (Type IV Gradation). From the test results, it is very clear that FA caused to reduce the compressive strength at all levels, except for 5% FA. This content may increase the compressive strength a little due to the increase in workability when compared with plain concrete. In general, FA contributes to the filler and pozzolanic effect in concrete. According to Jiang and Guan, the total porosity of the paste increased with increasing the fly ash content and w/b ratio and decreased with increasing age (Jiang ve Guan, 1999). Azhar et al (2000) reported that the addition of FA (20-30%) also decreased the compressive strength up to 25% at 28 days. The reduction in the compressive strength at 28 days is related to the properties of FA that decreases the heat of hydration of concrete.

The test results demonstrate that the addition of 10% SF to the mix resulted in increase at 28 day compressive strength. However, further addition of SF causes a reduction in the compressive strength of concrete pavement. Demirboğa reported that after 10% SF replacement for cement, compressive strength of mortars decreased with increase of SF replacement (Demirboğa, 2002). Moreover, Shannag also reported that the addition beyond 15% resulted a significant decrease in 28-day compressive strength (Shannag, 2000). As for the concrete with the SF, increase in the strength of concretes may be attributed to the improved aggregate – paste bond improvement that is associated with the formation of less porous transition zone in the SF concrete (Demirboğa, 2002).

ANOVA is an important statistical analysis and diagnostic tool which helps us to reduce the error variance and quantifies the dominance of a control factor. The column under the p% gives an idea about the degree of contribution of the factors to the measured response. If the p% is high, the contribution of the factors to that particular response is more and vice versa. Results of ANOVA showed that (Table 6),

Table 6. ANOVA table for determining the percent contribution of factors on Compressive Strength

ANOVA table after pooling							
Source	**Pool**	**DOF**	**Sums of Squares**	**Variance**	**F-Ratio**	**Pure Sum**	**Percent (P)**
Factor A	N	3	28.7	9.57	7.71	24.98	53.00
Factor B	N	3	7.26	2.42	1.95	3.53	7.50
Factor C	Y	(3)	3.02		Pooled		
Factor D	Y	(3)	3.91		Pooled		
Other/Error		9	11.17	1.24			3.50
Total		15	47.13				100.000

both w/b ratio and gradation type played significant role on 28-day compressive strength. Moreover, because of the effects of FA and SF was negligible, they were pooled. The contribution of the factors to S/N was given in Table 7.

Table 7. Optimum conditions for the maximum compressive strength according to Figure 1 and prediction of performance

Factors	**Level No**	**Contribution to the S/N**
A	1	0.917
B	4	0.624
C	2	0.499
D	2	0.939
Total contribution of all factors		2.979
Average performance statistic (S/N)		36.36
The expected value in optimum conditions (MPa))		60.04
Confidence interval (Confidence level α=95%) (S/N)		34.36 – 38.37
Confirmation test results (S/N)		36.5
Confirmation test results (MPa)		66.83

Factor values given in Table 7 are the optimum conditions that maximize the compressive strength. The numerical value of the maximum point in each graph marks the best value of that particular factor. The maximum values for each factor are given in Table 7. According to ANOVA results, w/b ratio, type of gradation, fly ash and silica fume content were to have the effect of 53%, 7% on the compressive strength. Being no influence of silica fume and fly ash means that any level of these factors can be used in concrete mix. However, in order to obtain maximum compressive strength, the levels that maximize S/N must be used. 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: 2 D: 2) was not performed during the experimental work. Thus, it should be noted that the compressive strength value 36.36 MPa given in Table 7 is the predicted result by using equation 2. Confidence interval of prediction at the 95% significance level is also given as 34.36 – 38.37 in Table 7, predicted from equation 3. In order to test the predicted result, confirmation tests were conducted twice at the optimum working conditions. From the fact that the compressive strength of 37.1 and 35.8, 36.5 being the average, obtained from the confirmation tests at the same experimental conditions as in Table 7 are well within the calculated confidence interval. It can be said that the experimental results are within ±5% in error. These results showed that the interactive effects of the factors are negligible for compressive strength of concrete and also prove that the Taguchi Method can successfully be applied to the compressive strength experiments in a shorter time with a very limited number of experiments.

CONCLUSIONS

- According to ANOVA results, significant factors affecting the compressive strength are water/binder ratio and type of gradation.
- The factor levels used in this study for FA content and SF content do not have statistically significant importance. This means that any level of these two factors can be used. However, the optimum conditions were found to be 0.30 water/binder 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, 5% FA content and 10% SF content for 28 days compressive strength.
- Compressive strength of 66.83 MPa was obtained at the optimum conditions.
- 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.

REFERENCES

Abou-Zeid M.N., Wojakovski J.B. and Cross S.A. (1996). High dosage type-c fly ash and limestone in sand-gravel concrete, *Transportation Research Board*,36.

Committee ACI 226. 1998. Use of fly ash in concrete, ACI 226.3R-87, *ACI Matter J*, 85, 381 – 408.

Ağar E., Sütaş İ. ve Öztaş G. (1998). *Beton Yollar*, İstanbul Teknik Üniversitesi İnşaat Fakültesi Matbaası, İstanbul.

Azhar S., Nimityongskul P. ve Poon C. (2000). Development of high performance dry premixed concrete, Cement and Concrete Technology in 2000s, *Proceeding of the Second International Symposium, Vol.2 Istanbul, Turkey*, 68 – 77.

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

Bayrak O. Ü. (2002). *Optimization of the some mechanical properties of concrete pavement mix containing fly ash and silica fume by Taguchi method*, MSc. Thesis. Atatürk University, Graduate School of Natural and Applied Science, Erzurum.

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

Bhanja, S. and Sengupta. B. 2002. Investigation on the compressive strength of silica fume concrete using statistical method, *Cement and Concrete Research*, 1391 – 1394.

Demirboğa, R. (2002). Influence of mineral admixtures on thermal conductivity and compressive strength of mortar, *Cement and Concrete Research*, 189 – 192.

Jiang L. and Guan Y. (1999). Pore structure and its effect on strength of high – volume fly ash paste, *Cement and Concrete Research*, 631 – 633.

Khatri R.P., Sirivivatnanon V. and Gross W. (1995). Effect of different supplementary cementitious materials on mechanical properties of high performance concrete, *Cement and Concrete Research,* 209 – 220.

Malhotra V.M. and Carette G.G. (1983).An efficient material.-silica fume concrete - properties, applications, and limi-tations, *Concr. Int. Design Constr.*, 5, 5, 40 – 46.

Peace, G. S. (1993). *Taguchi Method*, Corporate and Professional Publishing Group.

Poon C.S., Kou S.C., Lam L. and Lin Z.S. (2001). Activation of fly ash/cement systems using calcium sulfate anhydrite ($CaSO_4$), *Cement and Concrete Research*, 31, 873 – 881.

Roy, R. K. (1990). *A Primer on the Taguchi Method*, Competitive Manufacturing Series.

Sautsos M.N. and. Domone P.L.J. (1993). Strength Development of Low Water-Binder Ratio Mixes Incorporating Mineral Admixtures.2, *Proceedings of the 3rd International Symposium on the Utilization of High-Strength Concrete, V. 2, Lillehammer, Norway*, 945–952.

Senadheera S.P., Jayawickrama P.W. and ASMA R. (1996). Use of hydrated fly ash as a flexible base material, *Transportation Research Board*, 53.

Shannag, M.J. (2000). High strength concrete containing natural pozzolan and silica fume, *Cement and Concrete Research*, 399 – 406.

Srinivasan C. B., Lakshmi Narasimhan N. and Ilango S. V. (2003). Development of rapid-set high-strength cement using statistical experimental design *Cement and Concrete Research*, 33, 9, 1287 – 1292.

Targan Ş., Olgun A., Erdoğan Y. ve Sevinç V. 2002. Effects of supplementary cementing materials on the properties of cement and concrete, *Cement and Concrete Research*, 1551 – 1558.

Toutanji H.A. and El-Korchi T. (1995). The Influence of Silica Fume on the Compressive Strength of Cement Paste and Mortar *Cement and Concrete Research*, 25, 7, 1591 – 1602.

Yogendran V. Langan., B.W, Haque M.N., and. Ward M.A, (1987). Silica fume in high-strength concrete, *Materials Journal* 84, 124-129.

Whiting D. and Detwiler R. (1998). Silica fume concrete for bridge decks, *Transportation Research Board*, 1.

Wu Z. and Naik T.R. (2002). Properties of concrete produced from multicomponent blended cements, *Cement and Concrete Research*, 1937 – 1942.

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

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

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