Teaching the Taguchi Method of Experimental Design: Design and Testing of Concrete Mixes

Deborah J. Hochstein, Azmi Bin Ahmad, Robert E. Magowan
The University of Memphis

Abstract

The primary objective of this project was to demonstrate the Taguchi Method of experimental design for a graduate-level course entitled, “Advanced Statistical Quality Control”, at The University of Memphis. The nature of the project enabled students to participate in the entire process, from start to finish. This particular topic, design and testing of concrete mixes, was selected for two reasons. First, it involved several factors, both controllable and uncontrollable. Second, there is historical evidence of the constituents and proportions of a good mix. If the best design mix predicted by the experiment is consistent with the historical recommendation, it lends credibility to the Taguchi Method in the eyes of these students. If the students complete this exercise with a knowledge of the basic skills required for experimental design using the Taguchi method, and confidence in the method’s efficacy, then the pedagogical objective will have been met.

Introduction

Engineering science is well founded on the basic laws of nature which have been proven over time using the scientific method which requires that a hypothesis be proven by experimentation. At an introductory level, almost without exception, students are taught that the best way to conduct an experiment is to hold constant all variables except one, and to vary the remaining variable in order to reveal the dependence of the experiment’s outcome on that variable. While this method of experimentation, which requires a full factorial design, has served the scientific community well in academic environments, it has proven to be ineffective in the manufacturing environment. Performing experiments by varying one quantity at a time is far too costly in both time and money for most manufacturing firms. In addition, this method does not enable the engineer to observe the interaction between the quantities being varied. Dr. Taguchi, in the 1950’s, devised a partial factorial method of experimental design that requires far fewer trials than the traditional full factorial scientific method. His method combines engineering techniques with statistical methods in such a way that rapid improvements in quality and cost reduction occur when optimizing product designs and manufacturing processes. “Ford Motor Company was one of the first companies in the United States to recognize the value of Taguchi’s approach to quality. Ford brought Dr. Taguchi to Dearborn, Michigan, to teach its suppliers these techniques in 1981.” (Magowan, 1991). “The quality of Japanese automobiles is attributable largely to the widespread application of the Taguchi Method.” (Roy, 1990).

It is imperative that engineering students who plan to enter a manufacturing environment be provided with an opportunity to study this technique as an alternative to the traditional univariable approach. Application of Taguchi’s experimental design methodology early in the product’s design phase will facilitate the evaluation and comparison of design configurations and material selection. Used in the early phases of facility design, this methodology can improve process yields and reduce variability. “The use of experimental design in these areas can result in products that are easier to manufacture, products that have enhanced field performance and reliability, lower product cost, and shorter product design and development time." (Montgomery, 1991). In short, familiarity with methods of experimental design provides engineers with yet another tool to use to solve problems in a cost effective and timely fashion.

Concepts of the Taguchi Method

Taguchi developed a method of optimizing the process of experimentation in an effort to improve R&D productivity and enhance product quality while working for the Electrical Communication Laboratories in Japan, (similar to our Bell Laboratories). While there, he observed first hand the large amounts of time and effort being spent on experimentation and testing and came to believe that through creative brainstorming the expenditure of resources in this endeavor could be reduced. The result was a design philosophy that "has produced a unique and powerful quality improvement discipline that differs from traditional practices." (Roy, 1990). Taguchi emphasized that quality should be designed into the product, not inspected into it. Quality is achieved by specifying a target value for a critical property and developing manufacturing processes to meet that target with minimal deviation. This is in sharp contrast to the "goalpost philosophy" in which products are made within permitted tolerances as set by designers with little regard to critical properties from the customer's point of view (Ross, 1988). Taguchi also states that quality should be measured in dollars as it relates to the loss-to-society caused by a product during its life cycle. A truly high quality product will have a minimal loss-to-society. This loss can take the form of; poor performance resulting in returns, warranty service calls and/or product replacement; the cost of scrap, rework, and inspection; or globally in terms of pollution, noise, or diminished reputation. The implication is that the (loss-to-society) measured in dollars is proportional to the (deviation-from-target-value). (Ross, 1988).

"Taguchi built upon W. E. Deming's observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker." (Roy, 1990). Taguchi emphasizes the development of manufacturing processes that are "robust", or insensitive to variations in uncontrollable factors such as environment, and machine wear. This is accomplished through careful construction of tables known as "orthogonal arrays" (OA). The arrays are structured only after thorough evaluation of all the properties or factors which affect product quality, a process referred to as "brainstorming". The array can include factors which are controllable and those which are uncontrollable, (noise), as well a different levels for each factor. Each column in the array represents a factor, while each row represents an individual trial specifying the level of each factor. The number of elements in the array determines the number of experimental samples to be tested. Special care must be taken in constructing the array because it determines both the factors and interactions which will be examined and establishes the experimental procedure. Test results are entered into the array and an ANOVA analysis of the results yields valuable information regarding the optimum combination of factors and levels and demonstrates the interaction of these factors if any exists. It is important to note that while constructing the array the practitioner must take care to insure that the factors and interactions to be included in the array accurately reflect properties which affect the quality of the product or process. As is true with all experimental techniques, a poorly designed experiment, even if properly executed, yields results of questionable value.

Brainstorming

The students first learned that before an array could be structured, various factors, both controllable and uncontrollable, must be examined. This required some level of familiarity with the topic. The class was composed of both engineering technology graduate students and graduate students from the College of Business. While both groups knew that concrete is composed of cement, sand, gravel, and water, they all had to research factors which affect its strength. The design of a concrete mix depends upon many factors including; type and proportion of ingredients, additives to improve water-tightness or curing time, slump or workability requirements, humidity and temperature, and geometry of the form. After gathering information from a variety of engineering texts and interviewing both engineering faculty and construction firms, the students selected four controllable variables and three interactions, each with two levels, (Table 1), which resulted in a total of seven degrees of freedom. Hence an L8 orthogonal array was selected for the inner array. The four controllable factors were, regular tap water, (A), Portland cement (type I), (B), pea-gravel, (C), and sand, (D). The three interactions were between: water and cement, (AxB); water and coarse aggregate, (AxC); and cement and coarse aggregate, (BxC). The two uncontrollable (noise) factors were humidity, factor X, and temperature, factor Y. Studying the interaction between these noise factors required three degrees of freedom and consequently an L4 orthogonal array was selected for the outer (noise) array. The rationale was; if a concrete pour was to take place out-of-doors, weather would be uncontrollable. Although ANOVA and Taguchi methods are capable of handling far larger numbers of variables, confining this project to the selected group is consistent with the stated pedagogical goal.

FACTOR / DESCRIPTION	LEVEL 1	LEVEL 2
Controllable Factors		
A. Water	2.99 kg	3.68 kg
B. Cement	6.67 kg	7.36 kg
C. Coarse Aggregate (small rocks)	8.74 kg	9.66 kg
D. Fine Aggregate (Sand)	10.35 kg	11.96 kg
Uncontrollable (Noise) Factors		
X. Humidity	Room	High
Y, Temperature	50^oF	Room

Table 1. Factors and Their Assigned Levels

The design of a concrete mix to attain specific strength requirements is specified in the American Society of Testing Materials (ASTM) Standards. These specifications have been developed over time, using the classical technique of varying one factor at a time. The most important proportion is the ratio between the amount of water and amount of cement used in the mix. The lower the water-to-cement ratio, the higher the strength. This standard also describes the optimum conditions for curing concrete. To help ensure that the design strength is achieved, temperatures should not drop below
50^o F, and the atmosphere should remain humid. There are techniques which can be applied to freshly poured concrete to help control these factors. In dry environments the concrete structure can be kept continuously dampened with water. In cold environments the concrete structure can be kept warm with steam heat. Both of these techniques are expensive and money could be saved if a trial mix could be designed that would perform well in adverse environments. The students decided to run the experiment with two levels for each of the controllable factors. This

would provide four corresponding values for a traditional water-to-cement ratio, (Table 2). Using published literature students were able to estimate the strength of the concrete mix based only on type of cement and water-to-cement ratio (Keyser, 1986).

Water-to-Cement Ratio	Water Level A	Cement Level B	28-Day Strength (psi)
0.41	1	2	6,500
0.45	1	1	6,000
0.50	2	2	5,500
0.55	2	1	5,000

Table 2. Water-to-Cement Ratios and Their Design Strengths

The strength values were expected to decrease as the water-to-cement ratio increased. The test samples specified as cured in a high humidity environment were expected to have a higher than design strength, and those specified as cured in a low temperature environment were expected to have lower than design strength. Since the concrete industry designs trial concrete mixes based on the water-to-cement ratio, students were especially curious to see if the Taguchi Method demonstrated a significance in the level of water or cement, or demonstrated an interaction between water and cement, (AxB).

Designing the Experiment

A computer software package titled QT4 was used to facilitate the construction of the inner and outer arrays in the design of the experiment, the production of Experimental Run and Data Collection sheets to use during the mixing and testing phase, and the performance of an ANOVA analysis of the test results. An L8 orthogonal array was selected to accommodate the seven degrees of freedom which included the four controllable factors and three interactions. To determine their positions in the columns of the L8 array, an L8 linear graph was used, as illustrated in Figure 1. A point represents a controllable factor while a line connecting two points represents the interaction of those two factors.

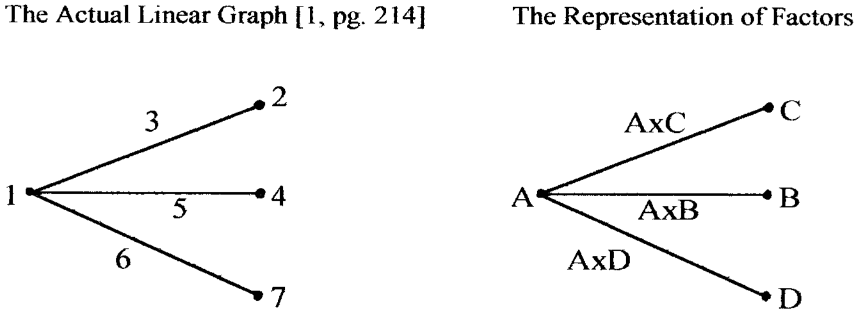
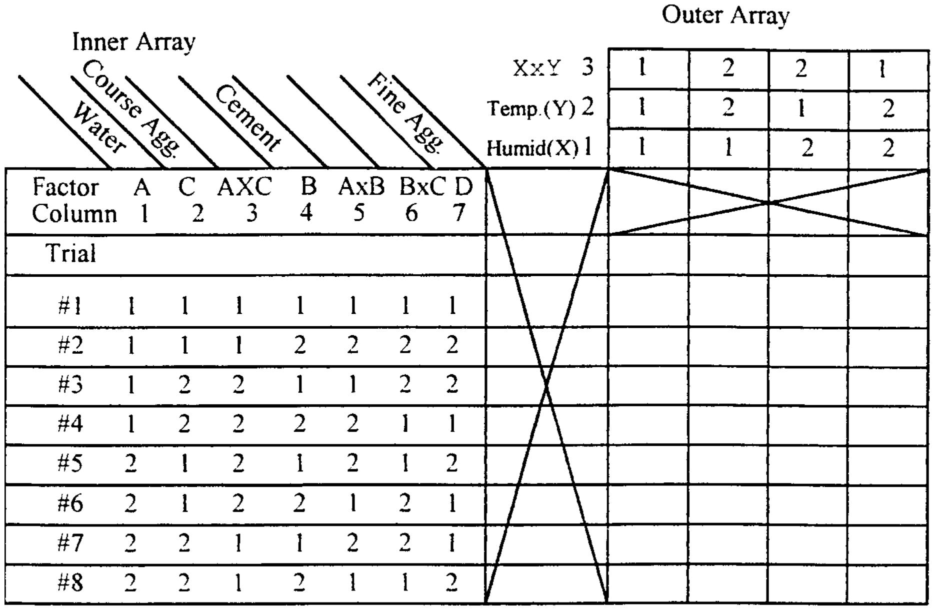


Figure 1. Linear Graph and its representation

An L4 outer array was selected to accommodate the three degrees of freedom associated with the two noise factors, humidity, (X), and temperature, (Y), and their interaction, (XxY). The combination of these inner and outer arrays resulted in the layout presented in Figure 2. This layout represents the trials at every level for each factor, to be performed.



XxY 3	1	2	2	1
Temp.(Y) 2	1	2	1	2
Humid(X) 1	1	1	2	2

Factor	A	C	AXC	B	AxB	BxC	D
Column	1	2	3	4	5	6	7
Trial							
#1	1	1	1	1	1	1	1
#2	1	1	1	2	2	2	2
#3	1	2	2	1	1	2	2
#4	1	2	2	2	2	1	1
#5	2	1	2	1	2	1	2
#6	2	1	2	2	1	2	1
#7	2	2	1	1	2	2	1
#8	2	2	1	2	1	1	2

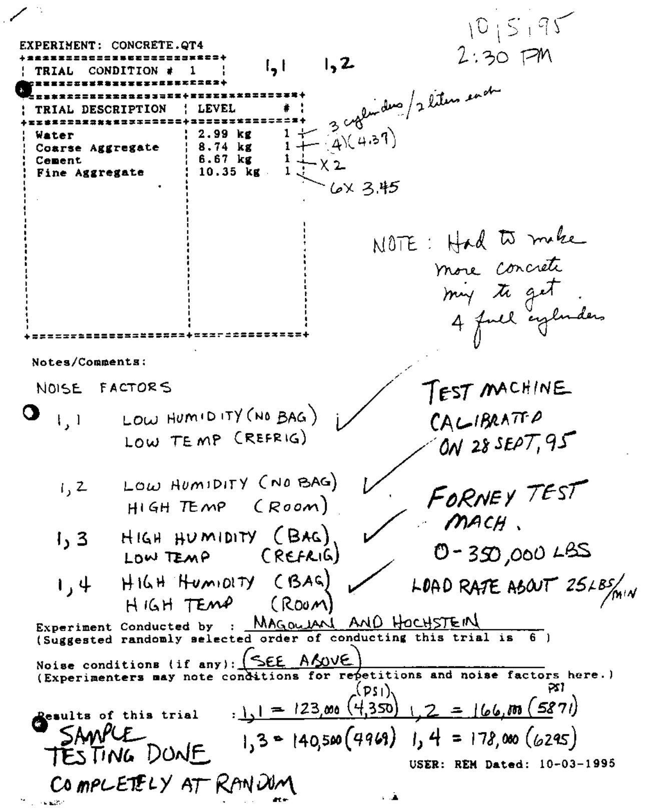
Figure 2. L8xL4 Layout

Without the orthogonal arrays, the minimum number of trials to obtain the full factorial ANOVA model would be (2^4 x 2^2) = 64 trials. The Taguchi Method clearly helped in designing this partial factorial ANOVA which reduced the number of trials to 32. This resulted in using less material, (thus reducing cost), less space for storing the specimens while they cured, (especially the cold ones in the refrigerator), and less time spent preparing the cylinders.

Running the Experiment

"Experimental Run and Data Collection" sheets, (Figure 3), were constructed for each of the eight trial mixes. The weight of each of the four materials and the corresponding level was specified. Sufficient concrete was made from the recipe to fill four test cylinders. The four test cylinders were labeled to identify the trial mix number and combination of noise factors. Observations about the conditions under which the test cylinders were prepared was noted on these sheets.

The measuring, mixing, rodding, pouring and clean-up activities for each trial mix were performed by students in the class under close supervision of the instructor. Care was taken to ensure that the individual mixes were made on a random basis and that the measurements were as accurate as possible. Water was measured with a graduated cylinder and the dry ingredients with a large balance scale. An electric concrete mixer was used to save labor and insure consistency in the mixing process. It was thoroughly cleaned between each mix to avoid contamination. Each cylinder was rodded at the one-third full point and full point per the ASTM standards to eliminate air pockets.



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EXPERIMENT: CONCRETE.QT4

TRIAL CONDITION # 1 1,1 1,2

TRIAL DESCRIPTION	LEVEL	#
Water	2.99 kg	1
Coarse Aggregate	8.74 kg	1
Cement	6.67 kg	1
Fine Aggregate	10.35 kg	1

3 cylinders/2 liters each
(4)(4.37)
X 2
6X 3.45

NOTE: Had to make more concrete mix to get 4 full cylinders

Notes/Comments:

NOISE FACTORS

1,1 LOW HUMIDITY (NO BAG)
LOW TEMP (REFRIG)

1,2 LOW HUMIDITY (NO BAG)
HIGH TEMP (ROOM)

1,3 HIGH HUMIDITY (BAG)
LOW TEMP (REFRIG)

1,4 HIGH HUMIDITY (BAG)
HIGH TEMP (ROOM)

TEST MACHINE CALIBRATED ON 28 SEPT, 95

FORNEY TEST MACH.
0-350,000 LBS

LOAD RATE ABOUT 25 LBS/MIN

Experiment Conducted by : MAGOWAN AND HOCHSTEIN
(Suggested randomly selected order of conducting this trial is 6)

Noise conditions (if any): (SEE ABOVE)
(Experimenters may note conditions for repetitions and noise factors here.)

Results of this trial : 1,1 = 123,000 (4,350) (PSI) 1,2 = 166,000 (5871) PSI
1,3 = 140,500 (4969) 1,4 = 178,000 (6295)

SAMPLE TESTING DONE COMPLETELY AT RANDOM

USER: REM Dated: 10-03-1995

Figure 3. Example Experimental Run and Data Collection Sheet

After two days of curing, the plastic molds were removed and the concrete cylinders were placed in the appropriate location for additional curing. Noise factors were produced using the facilities available to the department. The low humidity condition was achieved by leaving the cylinder exposed to the air. High humidity was achieved by placing the cylinder in a plastic bag with three cups of water and sealing it. Test cylinders with the designation, High Temperature, were left at room temperature. Test cylinders with the designation, Low Temperature, were placed in a refrigerator at approximately 50° F. As in conventional testing of concrete, the thirty-two test cylinders were left undisturbed for twenty-eight days while the curing process took place.

Preliminary Experimental Results

After 28 days, the cylinders were collected from their respective curing locations and a compression test was performed per the ASTM Standards to determine strength. A Forney Compression Testing Machine was used which allowed a compressive load to be applied at a slow constant rate until the maximum was observed. The cylinders were selected in a random order for testing. The maximum load for each cylinder was recorded on the Experimental Run and Data Collection sheet, (Figure 3) . The compressive strength was computed by dividing the load in pounds given by the dial indicator on the testing machine by the cross-sectional circular area, equation 1.

Strength = Load / Area (1)

Sample Calculation: Cylinder 4,1 Strength = (165,000 pounds) / 28.27 in^2 = 5,836 psi

The strength for each specimen was calculated and recorded in the L8xL4 orthogonal array, as shown in Figure 4. Averages for each trial were computed and some preliminary conclusions were made.

Inner Array	Water	Course Agg.		Cement			Fine Agg.	Outer Array				
X x Y								1	2	2	1	
Y								1	2	1	2	
X								1	1	2	2	
Factor	A	C	AxC	B	AxB	BxC	D					
Column	1	2	3	4	5	6	7					Average
Trial												
#1	1	1	1	1	1	1	1	4350	5871	4969	6295	5372
#2	1	1	1	2	2	2	2	5234	6048	5765	6861	5977
#3	1	2	2	1	1	2	2	5341	6826	5871	6861	6225
#4	1	2	2	2	2	1	1	5836	6791	6225	7392	6561
#5	2	1	2	1	2	1	2	3749	5022	4987	5659	4854
#6	2	1	2	2	1	2	1	4845	5447	4987	6543	5456
#7	2	2	1	1	2	2	1	3890	3926	4739	5659	4554
#8	2	2	1	2	1	1	2	4386	4633	4916	6331	5067

Figure 4. Scores and averages for each trial (not ranked)

Inner Array

Examination of the inner array reveals that water had the greatest influence on sample strength. At level 1, water gave higher average scores than level 2, while cement at level 2 gave higher average scores than at level 1. Very little difference could be observed for samples with different amounts of coarse aggregate and fine aggregate. To further confirm these preliminary results, students ranked the data according to strength, as illustrated in Figure 5.

Students observed that on ranked data, a pattern was formed involving the water column, A, and cement column, B. Three out of the first four highest ranked values had a water level of 1. Also, three out of four of the first four highest ranked values had a cement level of 2. This lead students to the conclusion that the level of water and cement had a considerable affect on the strength of the concrete mix.

Figure 5. Scores and Averages for each trial (ranked)

Students calculated averages for factors, (A), (B), (C), (D), at each level and interactions, (AxB), (AxC), (BxC), and recorded them in Table 3 and Table 4 respectively.

	A	B	C	D
Level 1	6033.5	5251.5	5414.5	5485.75
Level 2	4982.5	5765.25	5601.75	5530.75

Table 3. Level Average Table - Main Effects

When displayed in this fashion students could clearly see that factor A had the strongest effect with level 1 yielding a higher average than level 2. Factor B at level 2 also showed a slightly higher average than at level 1. Although the averages for factor C and D varied between levels 1 and 2, it was considered insignificant.

		A		B		C	
		1	2	1	2	1	2
A	1			5798.5	6269.0	5674.5	6393.0
	2			4704.0	5261.5	5155.0	4810.5
B	1					5113.0	5389.5
	2					5716.5	5814.0

Table 4. Averages of the Interaction Effects

The effects of the interactions were difficult to observe by inspection of the values in Table 4. Consequently, these values were put into graphical form, Figure 6 and Figure 7, so the interaction effects could be easily seen.

Figure 6. Response Graph for Main Factors.

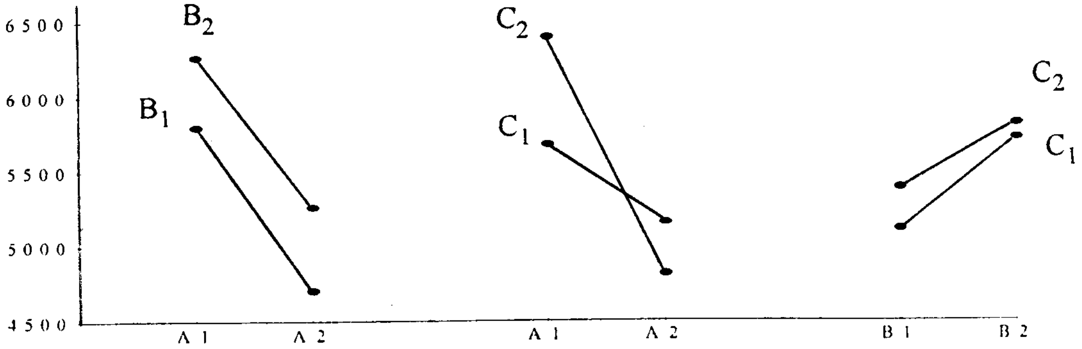

Figure 7. Response Graph for Interactions

The graph further supported the student's preliminary conclusion that, water, (factor A), has the strongest effect at level 1, followed by cement, (factor B), at level 2. Also, water, (factor A), and coarse aggregate, (factor C), showed some interaction, (AxC). The remaining interactions: water and cement, (AxB); cement and coarse aggregate, (BxC); did not show a notable effect.

Outer Array

Students also performed a preliminary analysis for the outer array factors, or noise factors of humidity, (X), and temperature, (Y). Table 5 contains the averages for the two factors at each level. Based on these averages the students arrived at another preliminary conclusion; both factors at level 2 showed higher strengths than at level 1. The graph of these averages is presented in Figure 8.

	X	Y
LEVEL 1	5137.2	5005.6
LEVEL 2	5878.75	6010.3

Table 5. The Averages for the Outer Array's Factors

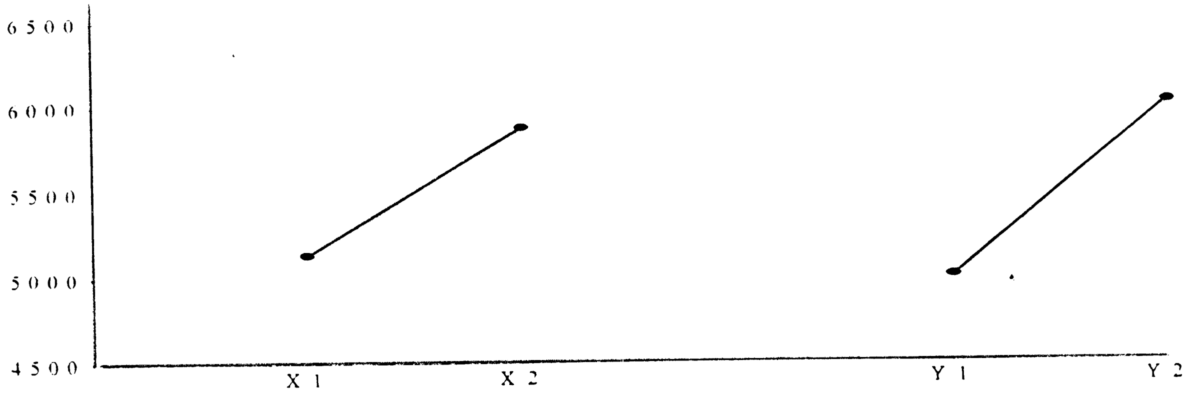

Figure 8. Response Graph for Noise Factors

Further analyses were made of the interactions of controlled factors (inner array) and noise factors (outer array). The averages of these interactions are presented in Table 6. The graphs for all of these interactions are presented in Figure 9 and Figure 10. Based on the results of these graphs, students concluded that the interactions of the noise factors and controllable factors did not appear to be significant. The only slight interaction might have occurred between water, (factor A), and Humidity, factor (X).

		A		B		C		D	
		1	2	1	2	1	2	1	2
X	1	5787	4487	4872	5403	5071	5204	5120	5155
	2	6280	5478	5630	6128	5758	5999	5851	5906
Y	1	5449	4562	4737	5274	4861	5151	4980	5031
	2	6618	5403	5765	6256	5968	6052	5991	6030

Table 6. Level Average - Countermeasures To Noise

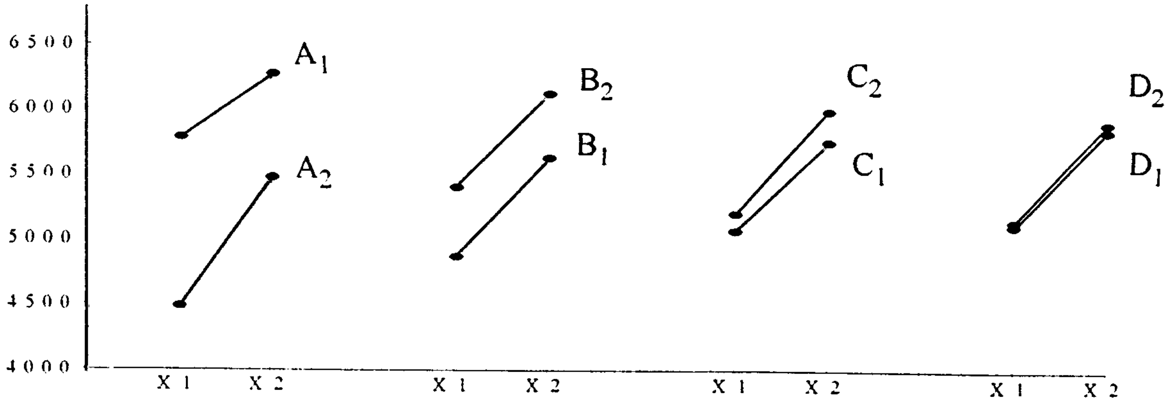

Figure 9. Response Graph for Interaction of Noise Factor X and All Controllable Factors

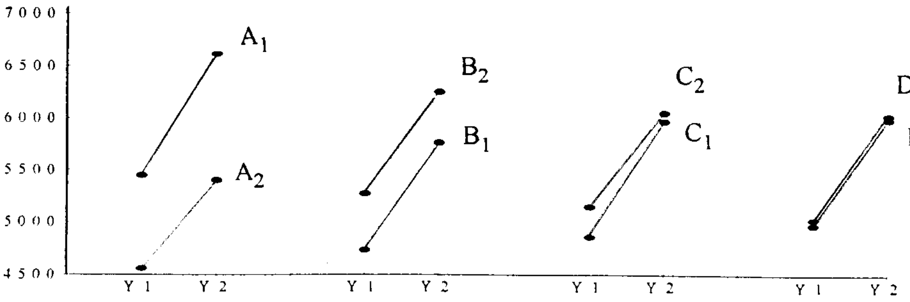

Figure 10. Response Graph for Interaction of Noise Factor Y and All Controllable Factors

Statistical Analysis of Results

Analysis of Variance and Signal to Noise Ratio

An Analysis of Variance of the measurements was performed using QT4 (Qualitek-4) computer software. The analysis was initially done with the assumption that the noise factors were not present to make data interpretation easier. Signal-to-noise ratios, and Analysis of Variance for the combination of noise factors and controllable factors, were later calculated to detect any noise variation in each trial.

S/N Ratio and ANOVA on Inner Array

An input dataset for QT4 was prepared containing the experiment data. Subsequent analysis showed that water had a significant effect on the strength of the concrete mix, (Table 7), at the 99 percent confidence level. ($F_{0.01,1,24}$ = 7.82 while $F_{0.05,1,24}$ = 4.26)

FACTOR	f	S	V	F	S’	rho%
A: Water	1	8.8379	8.8379	14.3337*	8.2213	28.9604
B: Cement	1	2.1141	2.1141	3.4288	1.4976	5.2754
C: Coarse Agg	1	0.2797	0.2797	0.4536	0.0000	0.0000
D: Fine Agg.	1	0.0166	0.0166	0.0269	0.0000	0.0000
AxB	1	0.0150	0.0150	0.0243	0.0000	0.0000
AxC	1	2.2627	2.2627	3.6698	1.6461	5.7987
BxC	1	0.0640	0.0640	0.1039	0.0000	0.0000
Error	24	14.7980	0.617			59.9654
Total	31	28.3883				100.00%

Table 7. ANOVA Table for Control Factors (unpooled)

Students calculated signal-to-noise ratios to observe the variation of the repeated data at each trial. These ratios reflect the variation in strength as a result of noise factors. The calculations were done using the following formula [Ross, 1988]:

$$S/N = -10 \log(1/r \sum 1/y_i^2)$$

Where r = 4 and y_i is the observation at each trial

TRIAL	A	C	AxC	B	AxB	BxC	D	S/N Ratio
1	1	1	1	1	1	1	1	14.3299
2	1	1	1	2	2	2	2	15.4071
3	1	2	2	1	1	2	2	15.7390
4	1	2	2	2	2	1	1	16.2364
5	2	1	2	1	2	1	2	13.4143
6	2	1	2	2	1	2	1	14.5633
7	2	2	1	1	2	2	1	12.8668
8	2	2	1	2	1	1	2	13.8484

Table 8. Signal-to-Noise Data

Data from Table 8 was used to perform the Analysis of Variance for Signal to Noise ratios to determine which of these variations were significant. The Analysis of Variance with these data is similar to the Analysis of Variance for an experiment with four factors and no repetitions. Without the repetition, the ANOVA was pooled to obtain the required F-statistic, shown in Table 9.

FACTOR	f	S	V	F	S′	rho%
A: Water	1	6.1538	6.1538	99.613*	6.092	63.14
B: Cement	1	1.7187	1.7187	27.822*	1.6569	17.17
AxC	1	1.5291	1.5291	24.753*	1.4673	15.20
Error	4	0.2471	0.0618		0.4326	4.48
Total	7	9.6487			9.6487	

* Significant at 99%

Table 9. Pooled ANOVA for S/N Ratio

Table 9, factor A, (water), factor B, (cement), and the interaction of factor A, (water), with factor C, (coarse aggregate), (AxC), are the only ones which are significant at the 99% confidence level. Factor A, (water), which accounts for 63.14% of the total variation in the eight signal to noise values, had the greatest difference. This means that factor A, (water) is the best controllable factor for maximizing the strength of the concrete in the presence of either of the two noise factors, low humidity or low temperature. Level averages can be derived for those factors that were significant. This is shown in Table 10. In any signal-to-noise analysis, the highest ratio determines the optimum factor and level condition.

	A	B		C1	C2
Level 1	15.4281	14.0875	A1	14.8685	15.9877
Level 2	13.6732	15.0138	A2	13.9888	13.3576

Table 10. Level Average Signal-to-Noise

The response graphs for the level of averages of the significant factors is shown in Fig 11.

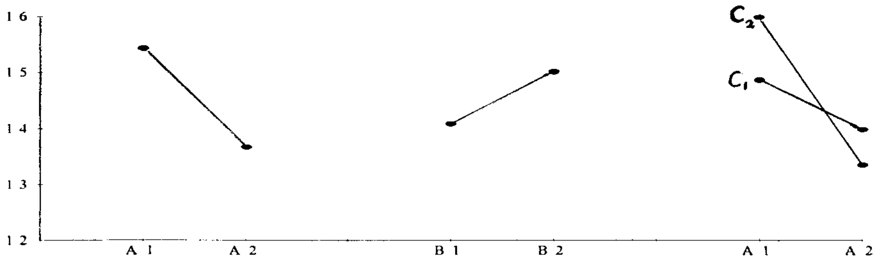

Figure 11. Response Graphs for Significant Factors - S/N Ratio

The optimum level of these controllable factors can be chosen by selecting the level with the highest average signal-to-noise value.

ANOVA on Inner and Outer Arrays

Sum-of-squares calculations were performed for all factors believed to have significant effects on strength, (Table 11). The calculation for combinations of controllable factors and noise factors is done in a slightly different manner, (Ross, 1988). Here, the inner array's sum of squares were calculated using one average value instead of the four repetitions. The sum-of-squares without the noise factors results are reported in Table 7. After obtaining these values, all the factors that were not found significant were pooled together with the error sum squares. The new ANOVA table is presented as
Table 12.

Source	df	S	V
A	1	2.20946	2.20946
B	1	0.52852	0.52852
AC	1	0.56565	0.56565
Error	4	0.09370	0.09370
Total	7	3.39734	3.39734
X	1	4.39932	4.39932
Y	1	8.07518	8.07518
AxX	1	0.49526	0.49526
AxY	1	0.21665	0.21665
BxX	1	0.00219	0.00219
BxY	1	0.00430	0.00430
CxX	1	0.02338	0.02338
CxY	1	0.08456	0.08456
DxX	1	0.00079	0.00079
Dxy	1	0.00026	0.00026
XxY	1	0.15248	0.15248
Error	14	11.6841	0.6873
Total	31	28.3883	

Table 11. Sum of Squares and Degree of Freedom for Combined Factors (controllable and noise)

Source	df	S	V	F	S′	rho%
A	1	2.20946	2.20946	4.514**	1.72002	6.06
X	1	4.39932	4.39932	8.988*	3.90988	13.77
Y	1	8.07518	8.07518	16.499*	7.58574	26.72
Error	28	13.7043	0.48944		15.17264	53.45
Total	31	28.3883	0.91575		28.3883	100.00

** significant at 95%
* significant at 99%

Table 12. ANOVA Table for Combined Factors (Pooled)

From Table 12 we can see that analyzing the variance by combining the controllable factors and the noise factors gives a slightly different result than would have been obtained if the analyses had been done one at a time, (with no combination). Calculating them one at a time could only describe part of the variation in the data, but analyzing them together gives a more accurate account of where the unexplained variations were. Furthermore, from Table 7, students can see that the explained variation or sum of squares for factor A (water) is not really obtained from factor A alone. In fact, the data shows some variation as a result of the noise factors. So, Table 12 distributes this variation appropriately. In other words, the sum of square or the variation in factor A from Table 7 contains variation from the noise factors and might not be as accurate as reported earlier. Also note that the percent of variation described by factor A (water) is only 6.06%, by factor X (humidity) is 13.77%, and by factor Y (temperature) 26.72%. This shows that temperature is the most important factor that would determine the maximum strength of the concrete mix. Although in earlier Analysis of Variance, factor A (water) is described as having 28.9604% influence to the overall strength of the concrete mix, it is a point of debate that the later Analysis of Variance, (Table 12), should be considered as a much more appropriate measurement.

Conclusion

From all these analyses, the students concluded that the maximum strength in a concrete mix can be obtained by setting; water at level 1, cement at level 2, coarse aggregate at level 2 and fine aggregate at level 1 or level 2. The optimum curing conditions are high humidity and high temperature. These conclusions are consistent with current practices in concrete mix design. Another positive outcome from this experiment is confidence in the average strength of the concrete mix even if the curing conditions are not optimal, (as long as they remain within the humidity conditions and temperature range tested).

The main objective of this exercise was to demonstrate the Taguchi Method of experimental design to a class of graduate students. To this end the activity was successful. The students gained valuable insight and experience in the Taguchi Method as they planned, designed, and ran the experiment. They were able to perform an analysis of the results and reached conclusions consistent with modern theory of concrete design. This project enhanced the students' confidence in the Taguchi Method and their ability to design an experiment.

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AZMI B. AHMAD

Azmi B. Amad earned a B.Sc. in Mathematics in 1985 from SUNY College at New Paltz, a a M.Sc. in Mathematics/Statistics in 1987 from West Virginia University, and has completed his third year in the Production and Operation Management Ph.D. program at The University of Memphis. He worked for six years as a lecturer in a Malaysian University (UUM) after completing his Masters degree. He has presented papers in conferences and published two college text books in Mathematics and Statistics. His research interests include Performance Measurement in Manufacturing, JIT, Quality Control and World-class Manufacturing. He is a member of APICS and Decision Science Institute.

DEBORAH J. HOCHSTEIN

Deborah J. Hochstein is an Assistant Professor of Manufacturing Engineering Technology at The University of Memphis. She received a B.S. in Physics from Georgian Court College and a M.S. degree from The University of Akron. She currently teaches courses in strength of materials and industrial materials. Her research interests include teaching methodologies in higher education, outcomes assessment and K-12 science education. She is a member of the Society of Manufacturing Engineers, American Society for Engineering Education, and Society of Women Engineers.

ROBERT E. MAGOWAN

Robert E. Magowan is a Professor of Manufacturing Technology at The University of Memphis. He received his bachelors and masters degrees from Eastern Kentucky University and his doctorate from Texas A&M University. He currently teaches courses in statistical quality control, production control systems, work measurement, and facility design. Over the years he has conducted a number of industrial seminars at The University of Memphis and in various plants and provided consulting services for companies in West Tennessee. He has also taught courses on the Taguchi Method for the Society of Manufacturing Engineers.