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Research Paper

Using the Taguchi Method to Optimize the Compressive Strength of Concrete in Different Aggregates Typology

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Abstract: Concrete quality is affected by many factors such as mixing ratios, material quality, transporting, placing and curing. One of the crucial factors that changes the compressive strength of concrete is aggregate which makes up 75% of concrete during concrete production. Properties of aggregate are more unstable than other materials depending on various reasons. Granulometry, moisture or organic substance amount of the aggregates which have same origin may differ within time. This study investigates physical and mechanical properties of crushed limestone and crushed river aggregates. It is on optimum design of concrete with crushed limestone and crushed river aggregates. At first, physical and mechanical properties of the aggregates are measured, then Taguchi method is applied. Test variables are water-to-binder ratio, cement dosage, river sand ratio to limestone and air entrained agent. L16 orthogonal array as an experimental design method is applied to determine the optimum concrete design in terms of compressive strength and flexural strength. Furthermore, contribution of variables on compressive and flexure strength is determined statically by using ANOVA method. Among the 4 different aggregate ratios evaluated in the study, the best performance is from the combination of 70% stream and 30% limestone. The weakest performance is from the series that do not contain any stream material.

Keywords: Taguchi, anova, concrete design, aggregate, mechanical properties

1. Introduction

Concrete is the second most commonly consumed material in the world after water. Aggregates constitute approximately 70-75% of the concrete volume. Aggregates are like skeleton of concrete and they are very effective on the performance of concrete with their properties. For concrete production, aggregates are generally selected from limestone-based crushed stone or materials obtained from the stream in the region for economical reasons. However, it is a fact that not all aggregates are suitable to produce concrete [1]. So, the properties of aggregates to be used in concrete should be known in detail. Cement that is used in the concrete composition is controlled strictly. Moreover, all cement manufacturers have R&D laboratories. In general, when a problem is encountered in concrete, the source of this problem is either mixing ratios or aggregate as the largest component. Concrete producers prefer aggregate sources close to urbanized areas for economical reasons. There are some researches on the evaluation of the use of existing aggregate resources in concrete. In a study examining the suitability of aggregate resources for concrete production in areas farther from the currently used resources in Isparta and its around, it has been concluded that a faraway gravel pit should start to operate for the sake of whole region [2]. Concrete producers especially prefer the nearby aggregate source, which constitutes approximately 75% of the concrete for economical reasons. In a study which looks at the physical and mechanical properties of aggregates taken from Kırıkkale Kızılırmak river, the usability of concretes produced in different granulometry compositions and different cement dosages in water structures is

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investigated. It concludes that the aggregate granulometry composition and the water/cement ratio and the effect of the curing environment on the concrete properties are important [3]. Akpar et al. [4] investigate the effects of three different aggregate types which are stream aggregate, limestone, and basalt, on concrete properties. In their studies, they obtain the highest strength values from basalt and the lowest values from stream aggregate. In another study comparing stream aggregate to limestone aggregate, it is concluded that stream aggregate has lower strength than the limestone aggregate similar to some other research [5]. In another study investigating the usability of the Yıldız River (located in the east of Yıldızeli district of Sivas province) sediments as concrete aggregate, as concrete, it is concluded that the frost resistance values of the Yıldız River sediments are outside the limits of TS 706, but other aggregate properties are compatible [6]. It has been determined that the materials in question will be used in Sivas and its around, and considering the climate of this region, low frost resistance values will create some problems. Some precautions are necessary to tackle the probable issues. Cavusoglu, et al. [7] investigate the usability of the crushed stream material which are processes in Kuşkayası quarry, and the material obtained from the Harşit stream (Giresun-Tirebolu) as aggregate. The data obtained as a result of their studies are compared with the data specified in the existing standards for aggregates and found compatible. In a thesis study conducted to determine the properties of materials extracted in Isparta region and used as aggregate in concrete production, the adequacy of aggregates taken from 5 different quarries is tested [8]. Then the suitability of the materials obtained from all aggregate quarries for concrete production is ranked from best to worst. In a study investigating the suitability of the aggregates obtained from the Yeşilırmak river for concrete production [9], it comes out that although the granulometric distribution of the aggregates related to the examined aggregate quarries is not suitable, it is suitable for concrete production due to its other properties and the compressive strength of the concrete produced with these aggregates is also sufficient.

The quality of the concretes used in the building is generally measured by their compressive strength. The fact that it achieves or goes beyond the target strength in terms of compressive strength shows that concrete can be used in the construction. It is a requirement of the project of the building to produce the concrete in the desired strength class. In order to produce concrete in the desired class, concrete producers generally change the water/cement ratio. It is rare to improve the characteristic properties of the aggregate. In this case, if there is a defect in the aggregate, it is compensated by adding more cement. Cement is the highest cost material among other components. The cost of concrete rises unnecessarily most of the times. When the samples were examined in Munzur University Building Laboratory, it was obvious that the average of the 3 samples sometimes met the target strength and even much higher However, the variance of the data in the calculation of average was higher than normal. This result may be due to the aggregate, so we prepare optimal concrete mix designs by determining all the characteristic properties of the aggregates used in concrete production and using the Taguchi experimental design. Then, we try to understand the effect of aggregate typology on concrete strength by making ANOVA analysis.

2. Material and Method

2.1. Materials

CEM I 42.5 cement produced in Elâzığ Cement Factory is used for the experiments. The water used in the mixtures is the city mains water. In order to determine the characteristic properties of aggregates used in concrete production samples were taken in accordance with TS EN 932-1 [10] for the experiments from each of the facilities where crushed limestone aggregate (CLA) from the mountain and crushed stone aggregate (CSA) from the stream are produced. The samples coming to the laboratory were used by reducing the amount needed in the experiments to be carried out by using the quartering method in accordance with TS EN 932-2 [11]. Figure 1a shows the image of the fine aggregates and Figure 1b shows the image of the coarse aggregates. The density of the air-entraining additive is 1.01 g/cm^3.

(a) (b)

Figure 1. CLA and CSA of different sizes

2.2. Aggregate Tests

First, the granulometry, unit and specific gravity and crushing resistance of the aggregates from two different sources are determined. In order to determine the grain size distribution (granulometric composition), particle classes and fineness modulus of aggregates to be used in concrete construction, sieve analysis test is applied in compliance with TS 706 [12]. Aggregate and compacted bulk density test is applied in compliance with TS EN 1097-3 [13]. Specific gravity and water absorption tests are applied in compliance with TS EN 1097-6 [14]. Two different test methods are used for fragmentation resistance. It is determined by Los Angeles and impact tests in compliance with TS EN 1097-2 [15].

2.3. Test Design

Five independent variables are selected for the study. These are cement dosage, water-cement ratio, air-entraining additive ratio, stream crushing-limestone crushing ratio and aggregate type. Table 1 shows selected independent variables and their levels.

Table 1 Test variables and their levels

Variable	**Level**			
	1	**2**	**3**	**4**
Dozage	400	350	300	250
W/C	0.58	0.53	0.48	0.43
Stream/Crush for Fine Ag.	1	0.7	0.35	0
Air-entraining %	0	0.05	0.1	0.15
Coarse Aggregate	River	Limestone		

If mixtures had been prepared with the traditional method instead of the Taguchi experimental design, 512 different mixtures would have to be made in order to fully determine the effects of these 4-level 4-factor and 2-level 1 factor. Taguchi's use of orthogonal indices in the experimental design matrices allows to determine with a mixture of 16 experiments as shown in Table 2.

Table 2 Taguchi L16 orthogonal experimental design matrix

	W/C	Dosage	Fine stream/limestone	Air-entraining	Aggregate Type
K1	1	1	1	1	1
K2	1	2	2	2	1
K3	1	3	3	3	2
K4	1	4	4	4	2
K5	2	1	2	3	2
K6	2	2	1	4	2
K7	2	3	4	1	1
K8	2	4	3	2	1
K9	3	1	3	4	1
K10	3	2	4	3	1
K11	3	3	1	2	2
K12	3	4	2	1	2
K13	4	1	4	2	2
K14	4	2	3	1	2
K15	4	3	2	4	1
K16	4	4	1	3	1

3. Findings and Discussion

3.1. Physical Properties of Aggregates

This study examines the effects of cement dosage, water/cement ratio and the effectiveness of the air-entraining additive material on the compressive strength which is the most basic concrete performance criteria of two different aggregate sources currently used in different concrete plants in the Tunceli region. The experimentally determined properties of crushed limestone obtained from the mountain and crushed stone obtained from the stream are summarized in Table 3. Two different test methods were used for wear resistance. The results of Los Angeles and impact methods confirm each other. Although both CSA and CLA materials have suitable values for concrete production, CSA material has lower fragmentation loss value. Both materials have physical properties suitable for concrete production.

Table 3 Some physical and mechanical properties of aggregates

	KKA			DKA		
	0-5 mm	5-15 mm	15-25 mm	0-5 mm	5-15 mm	15-25 mm
Los Angeles Frag. Loss (%)			24			16
Impact Loss (%)			7			5
Specific Gravity (g/dm^3)	2.63	2.60	2.60	2.72	2.66	2.65
Water Absorption (%)	2.20	2.02	1.25	1.46	1.35	1.05
Compacted Bulk Densitiy	1870	1480	1475	1680	1550	1540
Undamped Bulk Density	1639	1370	1363	1553	1408	1390

Figures 2 and 3 show CLA and CSA sieve analysis test results respectively. Optimum mixing ratios are determined with the aggregates used as divided into three different grain classes, and it is aimed to keep both aggregates in the ideal region and to be close to the B line in TS 706 [12]. The purpose of planning it close to the B line is to make it easier to pump.

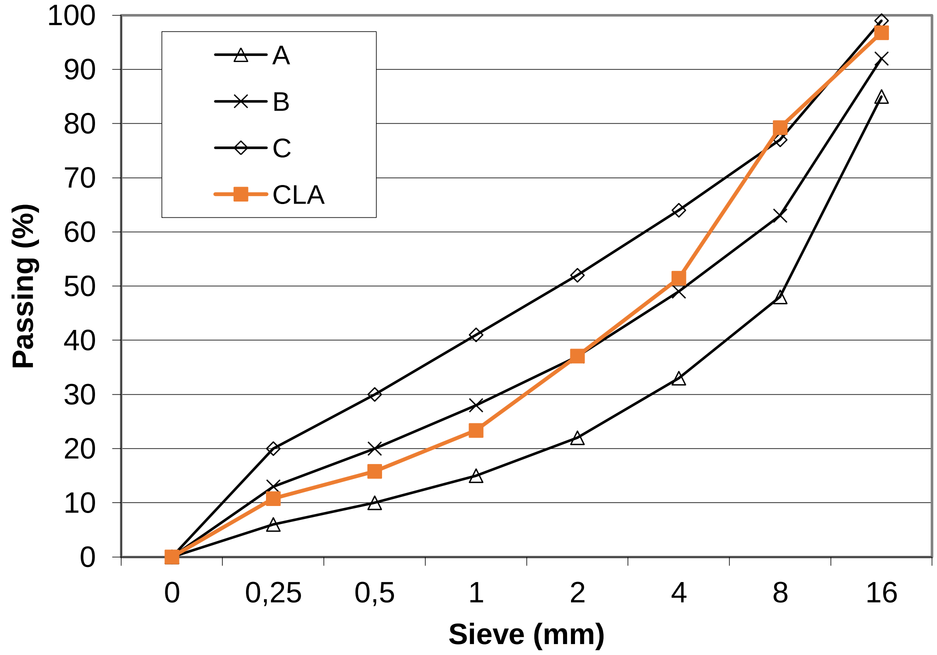

Figure 2. CLA granulometry test result

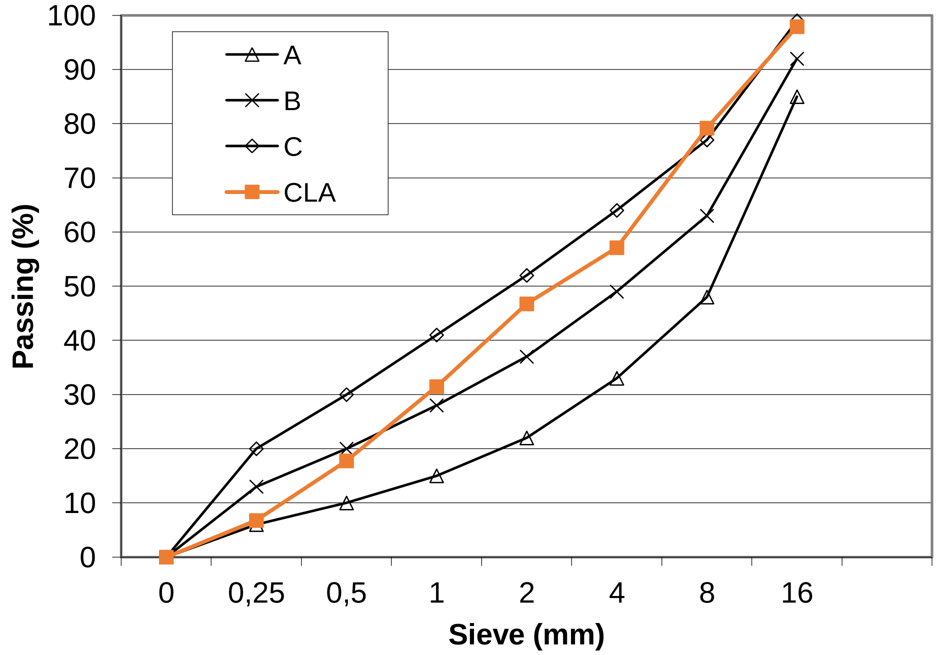

Figure 3. CSA granulometry test result

3.3. Fresh and Hardened Concrete Results

10 cm cubed specimens for compressive strength and 10x10x50 cm prism specimens for bending tests were prepared from each of the test series created according to Taguchi L16 orthogonal test design matrix. Standard compression and bending tests were performed after 28 days of curing. The amount of entrapped air for each batch was also measured in the fresh state (Figure 4). Table 4 shows the results. Figure 5 shows the Taguchi analysis results.

Figure 4. Measurement of the amount of air in fresh concrete

In the Taguchi Method, the analysis of the data obtained from the experiments is done with the help of a series of formulations. It is reported that various performance statistics have been developed that can be used depending on the problem studied [16]. The formula for the performance statistic, which is widely used as the optimization criterion (the larger the better) is given in equation 1. Here, Zb is the performance statistic, n is the number of repetitions in an experimental combination, and Yi is the performance value of the i'th experiment.

$$Z_b = -10Log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \quad (1)$$

Table 4 Result of experiment of hardened concrete

	Unit Weight g/dm^3	Air %	Compressive Strength N/mm^2	Bending Strength N/mm^2
M1	2456	3.9	30.10	4.928
M2	2309	5.5	22.97	4.658
M3	2220	6.1	14.07	3.915
M4	2149	6.5	11.30	2.835
M5	2398	3.2	37.80	4.590
M6	2306	4.6	29.63	3.780
M7	2398	2.3	33.50	4.523
M8	2288	5.5	28.70	4.388
M9	2361	4.9	45.87	4.118
M10	2269	6.2	33.67	4.590
M11	2217	5.5	27.03	4.928
M12	2330	2.5	32.30	5.670
M13	2390	3.5	50.30	7.425
M14	2398	2.7	49.07	6.070
M15	2288	5.5	35.80	6.010
M16	2325	3.6	38.77	6.210

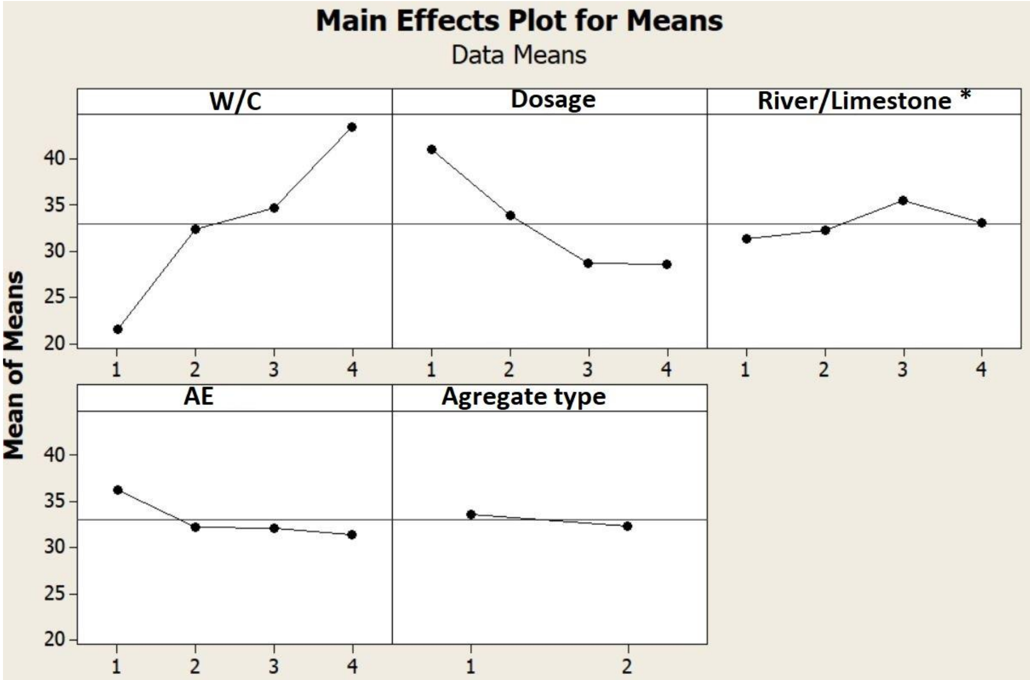

Figure 5. S/N ratios for compressive strength tests of experimental parameters

It is preferred that the concrete strength is high in compressive strength. Therefore, optimization is generally done according to the “the larger the better" situation. Accordingly, it is seen in Figure 4 that as the water/cement ratio decreases, higher compressive strength values are reached as expected. Although not as much as water/cement, it is known that the amount of cement in concrete affects the compressive strength of concrete. In this study, it is seen that the increase in dosage increases the compressive strength of concrete. According to the results obtained from the ANOVA analysis, it is seen in Figure 6 that the Water/Cement ratio with 65% and cement dosage with 23% have the greatest effect on the compressive strength.

In this study, where two different combinations of coarse aggregates, CSA and CLA, were tested to determine the effect of aggregate typology on compressive strength, it was observed that the samples prepared with CSA coarse aggregate reached slightly higher strength. In the ANOVA analysis, it is seen that the effect of this factor among all factors is at the level of 4%. There are studies in the literature showing limestone has higher performance [4,5,17,18]. The surface roughness of the crushed aggregate provides a strong mechanical bond between the aggregate and the hydration products of the cement. The larger the rough surface area, the greater the contact surface between cement paste and crushed stone aggregate. Due to the physical bond, it is seen that the strength of concrete produced with crushed stone aggregate is higher than concrete produced with rough stream aggregate. [19,20]. This situation emerges as an explanation of the fact that the direct use of stream aggregate in studies in the literature has lower results than crushed limestone. However, in this study, the fact that both types of aggregates were in the form of crushed stone enabled them to have similar surface roughness. However, unlike other studies, the aggregates used in this study have a rough surface feature as they are broken as in limestones. The effect level of the displacement of two types of aggregate in fine aggregate is at the level of 1%. The presence of air-entraining admixture in concrete seems to be more effective than the aggregate type. It was obtained as the optimum value that the fine aggregate was 35% stream and 65% limestone.

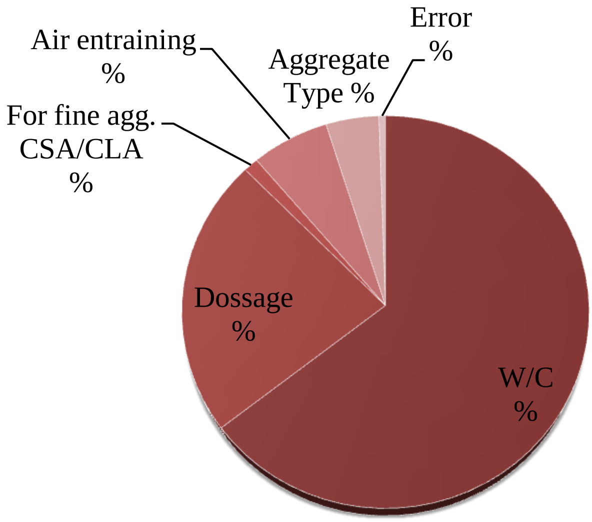

Figure 6. Effectiveness ratios of test parameters to compressive strength

4. Conclusion and Recommendations

This study includes experimental research on the adequacy of aggregates currently used in concrete production and their optimization in concrete design. There are two sources of aggregates of different origin that are generally used for concrete production. There is no problem in the manufacture of concrete separately with these sources, which are identified as streams and limestone. However, two separate aggregate sources have their own weaknesses. The weakness of the stream aggregate source is the scarcity of 0.25 mm sieve material. However, the strength limestone aggregate is lower compared to the stream. This research experimentally investigates whether the combined use of two aggregate sources will provide an improvement in the strength properties of concrete. Besides the aggregate difference, in order to see the effects of cement dosage, water/cement ratio and air-entraining additive at the same time, the number of samples is reduced with the Taguchi experimental design and the effectiveness rates are determined with ANOVA. Studies have shown that the combined use of aggregates performs better mechanically than single use. Among the 4 aggregate ratios evaluated in the study, the combination of 70% stream and 30% limestone has the best performance. The weakest performance comes from the series that do not contain any stream material. Although the stream aggregate is weak in many studies, the stream aggregate used in this study has higher strength due to crushed and therefore its rough surface. It is clearly understood that the facilities that produce with both types of materials can provide the target strength with a slightly higher cement dosage, as well as in a more economical way by adding other materials of origin in their mixtures.

Author(s) Contributions

TG contributes the idea of the study, the test design and its realization, and in the writing process of the article; SC contributes literature research, experimental studies and article editing.

Conflict of Interest

The authors declare that there is no conflict of interest.

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