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***Research Article***

# Strength Properties of Hardened Concrete Produced with Natural Aggregates for Different Water/Cement Ratios

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**Abstract**

Due to the competition in the concrete sector, there is a need for better quality and low-cost concrete production in recent years. One of the changes that can be made in this direction is the use of natural aggregates, which are expected to be particularly strong and obtained from river beds, in the production of concrete. It is intended to provide economic gain in Turkey, a country which is rich in terms of riverbeds, by evaluating these natural aggregates in the concrete production. It is common to use crushed stones as aggregates in concrete. However, such aggregates are difficult and costly to manufacture. Therefore, it is necessary to evaluate the existing natural resources efficiently. This study aims to investigate the effects of natural aggregates on hardened concrete properties. In the present study, quartzitic natural aggregates from the river beds in the Mediterranean region were used as aggregate. The experiments were carried out for different water/cement ratios by keeping the aggregate granulometry and cement dosage constant. A number of concrete samples produced within the scope of this study were subjected to hardened concrete tests such as compressive strength and splitting tensile strength. The results obtained are in accordance with the relevant TS standards. Thus, it was determined that these aggregates could be used in concrete for concrete strength. The strength of concrete samples and water/cement ratio were determined to be inversely proportional. In addition, a good fit was achieved between the results obtained from the compressive strength and splitting tensile strength tests.

**Key words:** Natural aggregate, hardened concrete properties, water/cement ratio, compressive strength, splitting tensile strength.

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# 1. Introduction

Following the discovery of cement, it was tried to define characteristics such as hardening, hydration heat, swelling, and shrinkage. The current concrete technology has been reached over time with the improvement of these characteristics. Studies are still in progress to find the most economical and optimum method to increase the workability and strength of concrete. The most important characteristics that should be found in a quality concrete are workability in the fresh state, mechanical strength in the hardened state, and durability against environmental conditions. Fresh concrete should not decompose and lose its homogeneity during the mixing, carrying or placing processes. Since concrete is a carrier material, it must be able to withstand the projected strength safely. Concrete should be resistant to external influences such as air, water, and environment, physical effects such as freeze-thaw, and wetting-drying, and deteriorations resulting from chemical reactions between aggregate and cement arising from its internal structure.

Concrete is the most commonly used building material in our day. Its main components are cement, water, and aggregate, and chemicals and other additives can be added when it is needed to obtain the desired properties. Since aggregates, one of these components, form a large part of concrete, they directly affect all the properties of concrete along with its strength. Aggregates provide good volume stability to concrete. Durable aggregates ensure that the concrete is more resistant to environmental influences. In addition, properties such as workability of the concrete, pumpability and the amount of air in the concrete are determined by the aggregates used (Erdogan, 1995).

Aggregates to be used in concrete must have a hard-breaking, hard-wearing, solid and hard structure. Abrasion resistance, compressive strength, toughness, and hardness of aggregate are the main factors affecting the mechanical properties of concrete. In general, the strength of the aggregates depends on the mineral composition, texture and structure of the rock from which they are obtained. A low resistance occurs as a result of the weakness of the components of the inner structure and their inability to be sufficiently connected to each other. According to the literature, the compressive strength of the aggregates used in concrete is about 200 MPa. Aggregate strength as well as aggregate granulometry, grain shape, surface structure, and the presence of harmful substances can directly affect the properties of concrete (Apaydin, 2007).

In the literature, it was determined that the adherence between aggregate and cement paste was high in the concrete mixtures produced with aggregates with high water absorption rates. Also, it was reported that the adherence resistance was inversely proportional to the compressive strength (Kawakami, 1992).

When the effect of the water/cement ratio on concrete compressive strength was examined, it was seen that the changing water/cement ratio varied up to 20 MPa depending on the type of aggregate. In the study conducted using different aggregate types, it was emphasized that the aggregate and cement transition zones showed different characteristics according to the natural structure of aggregates (Alexander and Milne, 1995). In addition, it was seen that as the cement dosage increased, the mechanical properties of the concrete improved (Tunc, 2018). Although the same mixture ratios were used in concrete mixtures formed by using different origin aggregates, it was determined that the compressive strength varied at the rate of 30%, and the bending strength at the rate of 40%. In addition, it was stated that the properties of the aggregate such as surface structure, shape, and modulus of elasticity had a great effect on the mechanical properties of concrete (Kaplan, 1959).

The effects of aggregate types with different chemical and mineralogical structures on the concrete strength were investigated. It was stated that the best concrete properties were obtained by using aggregates containing $SiO_2$ (silicon dioxide) at the rate of 80-95% and $CaCO_3$ (calcium carbonate) at the rate of 0.5-3.4% (Özkahraman and Işık, 2005). This showed that $SiO_2$ had a positive effect on the aggregate strength and therefore the concrete produced from this aggregate would be resistant. However, $CaCO_3$ is a component that lowers the aggregate strength. The quartzitic natural aggregates used in the present study have a high $SiO_2$ ratio.

It is seen that the compressive strength of the concrete containing large diameter aggregates is lower than that of the concrete containing small diameter aggregates. This is because the surface structures and shapes of aggregates are not suitable for mechanical coupling (Cetin and Carrasquillo, 1998). When the mechanical properties of concretes produced with different types of aggregates, including natural aggregates, are examined, it is seen that the results will be the basis for the damage mechanics model and fracture mechanics model etc. (Huang et al., 2018).

Tuğrul Tunç (2018) investigated the hardened concrete properties of concrete specimens produced using basalt aggregates belonging to a particular region. The compressive strength of the concrete containing the basalt aggregate was generally higher. It was concluded that the concrete produced by basalt aggregates may have better mechanical properties.

Positive results were obtained in a review study where the effects of waste aggregates on the compressive strength of concrete were analyzed. It was determined that the waste aggregates improved the concrete strength. The study also includes a discussion about the importance of environmentally friendly and economical concrete production (Tunc, 2019).

The concrete production was made by using crushed-stone and the effects of crushed-stone aggregates on the concrete properties were investigated in most of the studies related to the subject in the literature. It is difficult and expensive to supply and manufacture crushed-stone aggregates which are commonly used in concrete. A number of concrete samples produced with natural aggregates from the river beds were subjected to hardened concrete tests in the present study. Thus, it was aimed to investigate the usability of these natural aggregates in concrete and their effect on the concrete strength. It was aimed to achieve economic gain by ensuring that these aggregates are safely used in concrete in case the results obtained from the concrete produced with these natural aggregates were in accordance with the relevant standards. Also, it was aimed to determine the effect of water/cement ratio on the concrete strength.

## 2. Concrete Strength

Concrete strength is defined as the maximum resistance that concrete can show against the deformations and fractures due to the loads on it (ACI Committee 116, 1994). Compression, bending, and tensile strengths are the mechanical properties of the concrete. Because concrete is a brittle material, its compressive strength is higher. Therefore, the compressive strength is more important than other mechanical properties.

While the aggregate and cement paste exhibit a linear elastic behavior under load, the tensile value of the concrete shows a non-linear behavior with deformation (Figure 1). This non-linear behavior arises from the presence of aggregate and cement paste interface and the formation of microcracks on this surface (Shah and Winter, 1968).

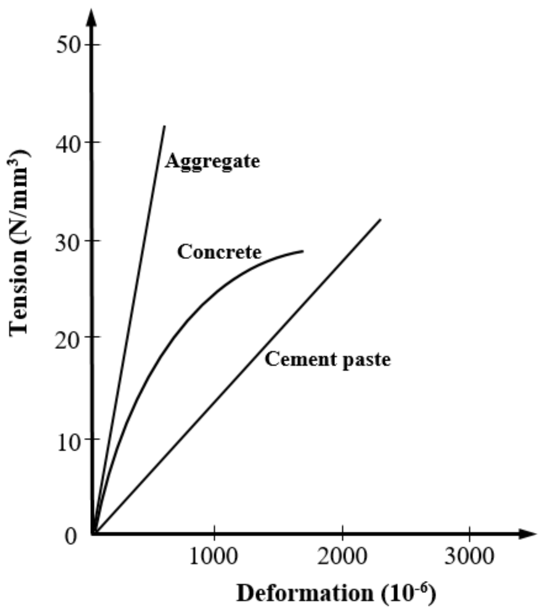


***Figure 1.*** *Tensile-Deformation correlation (Apaydin, 2007)*

There are many factors affecting the compressive strength of concrete. Among these, the type and ratio of materials can be classified as internal factors, and the effects that they will be exposed to during the production, maintenance and service life of concrete can be classified as external factors. Therefore, cement type, water/cement ratio, aggregate properties, chemical or mineral additives, the void structure of the concrete etc. can be given as examples of internal factors affecting compressive strength of concrete. However, concrete casting, curing temperature, curing conditions, and experimental conditions etc. can be given as examples of external factors (Mehta and Monteiro, 1997).

There are two important factors that primarily affect the compressive strength of the concrete with specific properties. These are the water/cement ratio and compaction of concrete (Ekinci and Kelesoglu, 2014). The compressive strength of a fully compacted concrete is inversely proportional to the water/cement ratio (Neville, 1981). Figure 2 shows the correlation between the compressive strength and the water/cement ratio.

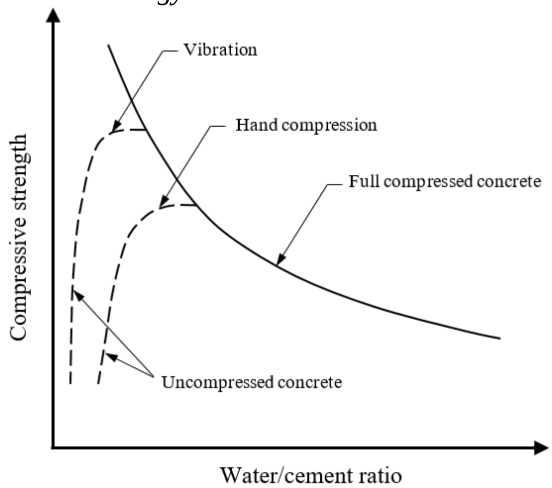


***Figure 2.*** *Change in the compressive strength with the water/cement ratio (Apaydin, 2007)*

One of the first equations to determine the compressive strength of concrete was given in the study by Abrams (1919). As seen in the Equation (1), the w/c was taken into account as the only parameter that affected the compressive strength.

$$f_c = \frac{K_1}{K_2^{(w/c)}} \tag{1}$$

where $f_c$=compressive strength (MPa), $w/c$=water/cement ratio by mass, $K_1$, $K_2$=empirical coefficients.

## 3. Materials and Methods

### 3.1. Aggregate

In the present study, natural aggregates with quartzitic content obtained from Mediterranean Region river beds were used as aggregates in concrete (Figure 3).

***Figure 3.*** *Natural aggregates used in the present study which are obtained from a river bed*

Aggregates having a maximum grain diameter of 16 mm were used as coarse aggregates and those having less than 4 mm grain diameter were used as fine aggregates in this study. Table 1 shows the physical properties and chemical contents of these aggregates. The specific weight values of normal concrete aggregates are between 2.2-2.7 g/cm$^3$ in the standards. The high specific gravity of these aggregates indicates that they are robust and good quality. In addition, water absorption rates are lower than those of other aggregates in the literature. A low aggregate water absorption rate is a desirable characteristic. Because the aggregates with high water absorption rates can easily crack and become deteriorated in severe weather conditions (freezing, wetting, drying, etc.). However, the adherence resistance between aggregates with higher water absorption rates and cement paste is also low. In addition, the high $SiO_2$ content in their chemical content indicates that these aggregates are robust and resistant.

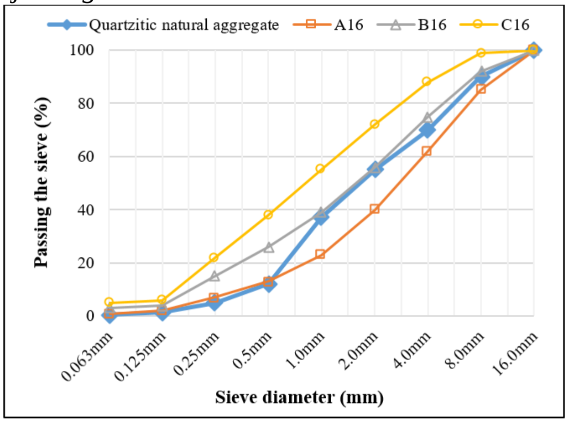


***Figure 4.*** *Granulometry curves of quartzitic natural aggregates*

***Table 1.*** *The physical properties and chemical compositions of the aggregate*

| Physical properties | | | | Chemical composition* | | | | |
|---|---|---|---|---|---|---|---|---|
| $B_{coarse}$ (g/cm$^3$) | $W_{coarse}$ (%) | $B_{fine}$ (g/cm$^3$) | $W_{fine}$ (%) | $SiO_2$ (%) | $Fe_2O_3$ (%) | $Al_2O_3$ (%) | CaO (%) | $Na_2O$&$K_2O$ (%) |
| 2.60 | 0.47 | 3.10 | 1.93 | 95-99 | 0.3-1.3 | 0.1-2.8 | 0.2-2.4 | 0.2-1.5 |

*Chemical content values are the mean values received from the General Directorate of Mineral Research.

where $B_{coarse}$=bulk density of the coarse aggregate, $B_{fine}$=bulk density of the fine aggregate, $W_{coarse}$=water absorption ratio of the coarse aggregate, $W_{fine}$=water absorption ratio of the fine aggregate.

Because the aggregates used in this study were obtained from a stream bed, they were very clean and smooth shaped. In addition, it was seen that the maximum compactness, which is very important in terms of granulometric distribution, was ensured. The fact that, among the aggregates, aggregates obtained from river beds have the highest compactness is also supported by other studies the literature (Yazıcı, 2006). The granulometry curves are drawn to determine the granulometry composition of aggregates. As stated in TS 706, the area between the A-B curve is the most suitable area for the usability of aggregates in concrete. The region between the curves B and C also shows usability.

As is seen in Figure 4, since the granulometry of the aggregates used in the present study is between the curve $A_{16}$-$C_{16}$, it was determined that maximum compactness was ensured, and these aggregates could be used safely in concrete. In Figure 4, the curves A, B, and C are the granulometry limit curves. The sieve diameters used in the analysis are between 0.063 mm and 16 mm.

## 3.2. Cement

CEM I 42.5 N Portland cement was used in this experimental study. The physical, chemical and mechanical properties of this cement type are presented in Tables 2-4. According to TS EN 197-1, it is desirable that the hardening in Normal Portland cement does not start before 1 hour but finishes before 10 hours. The hardening time of the said cement type is in this range (Table 2).

***Table 2.*** *Physical properties of the cement used in the present study (Tuğrul, 2015)*

| Specific weight (g/cm$^3$) | Onset of hardening (min.) | End of hardening (min.) | Fineness (cm$^2$/g) |
|---|---|---|---|
| 3.03 | 155 | 210 | 3490 |

In Table 3, the chemical composition of the cement used in this study covers results in accordance with the TS EN 197-1 standard.

***Table 3.*** *Chemical composition percentage by mass of the cement used in the present study (Tuğrul, 2015)*

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $Cl^-$ | Insoluble matter | Loss of ignition |
|---|---|---|---|---|---|---|
| 21.12 | 5.62 | 3.24 | 62.94 | 0.0044 | 0.64 | 3.52 |

Table 4 shows that the compressive strength values of the said cement were higher than the values stated in the TS EN 197-1 standard and therefore it can be used in the concrete production.

***Table 4.*** *The compressive strength of the cement (Tuğrul, 2015)*

| | 2-day (N/mm$^2$) | 7-day (N/mm$^2$) | 28-day (N/mm$^2$) |
|---|---|---|---|
| Present study | 25.8 | 38.1 | 49.1 |
| TS EN 197-1 | 20.0 | 31.5 | 42.5 |

### 3.3. Design and preparation of samples

In the present study, the cement dosage was taken as 400 kg/m$^3$. The amounts of use of coarse and fine quartzitic natural aggregates obtained from the stream bed were determined. The cubic sample of 150×150×150 mm in size was used in the concrete casting. The saturated dry surface specific gravity of the aggregates used in the mixture and three different water/cement ratios were taken into account. When other parameters were kept constant, only the water/cement ratios were changed, and four samples were cast for each water/cement ratio. A total of 24 concrete samples were cast, including 12 concrete samples to be used in the compressive strength tests and 12 concrete samples to be used in the splitting tensile strength tests. Thus, it was planned to investigate the effect of water/cement ratio on the concrete strength. Table 5 shows the aggregate (coarse-fine), cement and water weights that comprise the concrete mixture.

***Table 5.*** *Concrete mixture compositions*

| Cement (kg/m$^3$) | Coarse (kg/m$^3$) | Fine (kg/m$^3$) | Water/cement |
|---|---|---|---|
| 400 | 251.8 | 1761.4 | 0.50 |
| 400 | 244.2 | 1707.9 | 0.55 |
| 400 | 236.6 | 1654.4 | 0.60 |

A mixer with a vertical axis and rotating at an average speed of about 1.5 rev/sec was used to prepare the concrete samples with the mixing ratios determined (Figure 5a). First, cement and aggregate were added to the mixer and mixed in the dry state for about 1 minute. Then, half of the water to be used was added and continued to be stirred for 1 minute. The mixer was stopped when the sufficient homogeneity was obtained. The prepared concrete mixtures were filled into the cubic sample molds of 150×150×150 mm in size (Figure 5b). After 24 hours, the samples extracted from their molds were kept in the curing pool at 23±2°C for 28 days (Figure 5c).

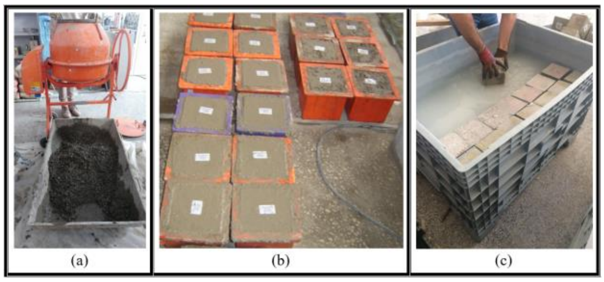

***Figure 5(a-c).*** *Images of the experimental study*

### 3.4. Test setup

The compressive strength of concrete is the resistance that the concrete can show to not break under the axial pressure load, namely, the maximum tension in concrete. Because there is an approximate correlation between the compressive strength and other strengths of concrete, the compressive strength of concrete is based on the design of almost all structures. Hardened concrete samples are subjected to breakage under uniform pressure load by means of a device called test press after 28 days in the curing pool as specified in the concrete standards. The compressive strength test was carried out in accordance with the TS EN 12390-3 standard. Before starting the compressive strength test, an excellent smoothness was provided for applying the distributed axial load uniformly to the upper and lower surfaces of the concrete samples. The steel loading plates of the test press and the sample surfaces in contact with them were thoroughly cleaned. One of the surfaces of the cube test samples perpendicular to the casting direction was placed vertically on the bottom plate. The sample was moved slowly to allow the press to coincide with the center of the spherical top plate. The loading was continued at a constant speed and in a way not to cause an impact until the sample was broken. The load shown by the press as soon as the sample breaks is the maximum load at the time of breaking. Following the completion of these procedures, the compressive strength of the sample was calculated by dividing the maximum load at the moment of breaking by the cross-sectional area vertical to the load application direction. Figure 6a shows the compressive strength test application mechanism.

The compressive strength and splitting tensile strength of concrete are closely correlated. The tensile strength of the concrete is about 7-17% of the compressive strength depending on the quality and age of the concrete. The splitting tensile strength test was carried out in accordance with the TS EN 12390-6 standard. During the application of the test, the sample was placed parallel to the lower plate of the test press as shown in Figure 6b. About 25 mm wide and 3 mm thick plywood sticks were placed on the upper and lower parts of the sample surfaces. Then the pressure load was applied via the test press. The load required to divide the cubic samples into two parts was determined. The splitting tensile strength was calculated by dividing this load into the cross-sectional area.

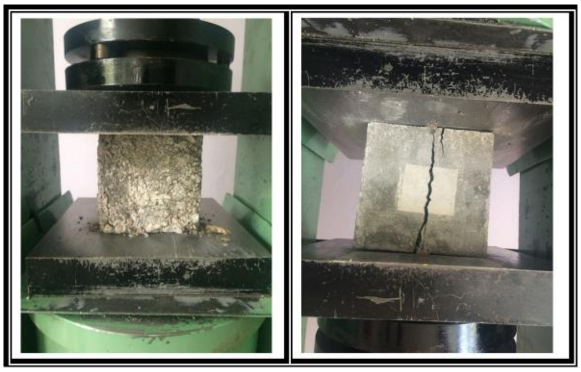

***Figure 6.*** *Hardened concrete tests: a) Compressive strength test, b) Splitting tensile strength test*

## 4. Experimental Findings and Discussion

Figure 7 shows some of the samples divided into two parts from the middle after being subjected to the tests. When the broken sample surfaces are examined, the natural aggregates can be seen clearly. In addition, it can be seen that there is not much damage, wear, and disintegration in these aggregates. This shows that the aggregate type used is resistant.

***Figure 7.*** *Broken sample surfaces*

In this experimental study, the effects of changing water/cement ratios on the compressive strength and splitting tensile strength were investigated by keeping the parameters like cement dosage ($C$=400 kg/m$^3$), cubic sample sizes (150×150×150 mm), and aggregates granulometry ($D_{max}$=16 mm) constant. Figure 8 shows the compressive strength values of 4 samples prepared for each *w/c* provided that other parameters are constant. For *w/c*=0.50 the compressive strength values of the samples showed a maximum change of 12%. However, for *w/c*=0.55 and 0.60, the maximum change in the compressive strength values of the samples was 3%.

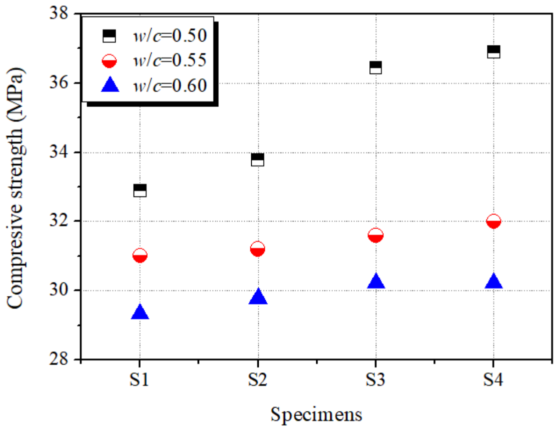


***Figure 8.*** *Compressive strength values of concrete samples prepared under the same conditions for different w/c ratios*

Figure 9 shows the splitting tensile strength values of the samples. It was seen that the least margin of error was for *w/c*=0.55 with a maximum change of 5% in the results. In the other series, however, the maximum change in splitting tensile strength values of the samples was found to be 12%.

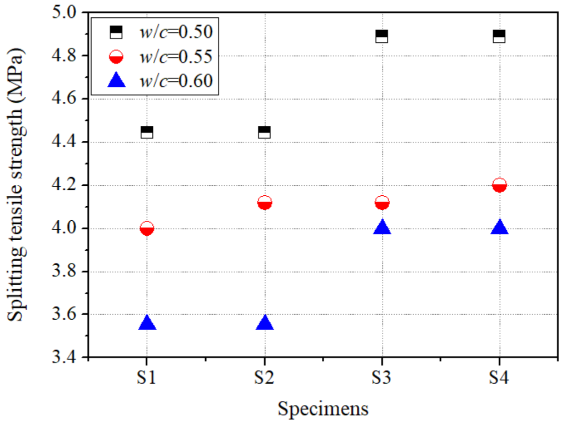


***Figure 9.*** *Splitting tensile strength values of concrete samples prepared under the same conditions for different w/c ratios*

All concrete samples tested had a linear change and a good correlation ($R^2$=0.92) between the compressive strength and splitting tensile strength values. In total, a maximum increase of approximately 37% was measured in the tensile strength in response to a maximum increase of 26% in the compressive strength (Figure 10).

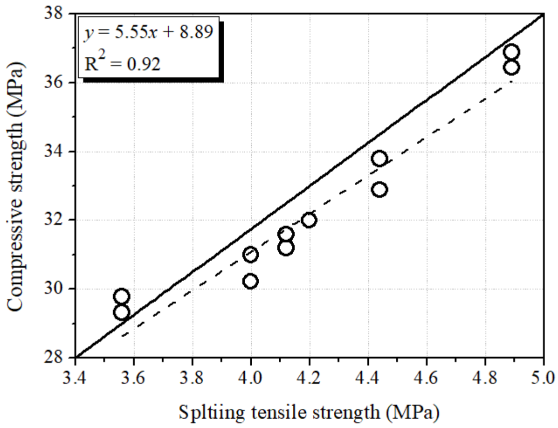


***Figure 10.*** *Correlation between the compressive strength and splitting tensile strength in the present study*

Figure 11 shows the mean compressive strength values with the change in the *w/c* ratio. It is seen that this graphic is very close to the one in Figure 2 and, hence, it can be said that the results of the present study were quite in accordance with the literature. In this study, an inverse proportionality was determined between the compressive strength and water/cement ratio. In addition, it is understood that from Figure 11 that the concrete samples in question were completely compressed.

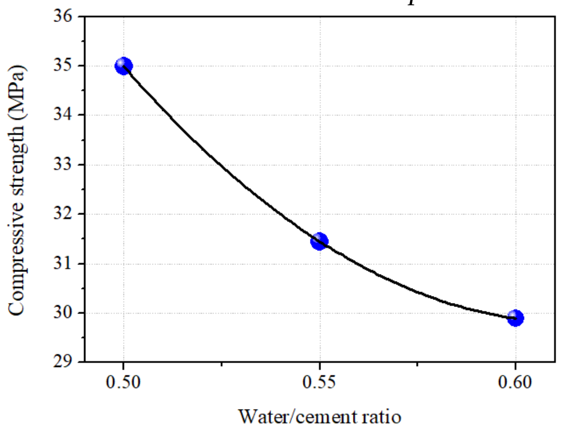


***Figure 11.*** *Change in the compressive strength with the water/cement ratio in the present study*

In Figure 12, however, there is an inverse proportional change between the splitting tensile strength and the water/cement ratio similar to that in Figure 11.

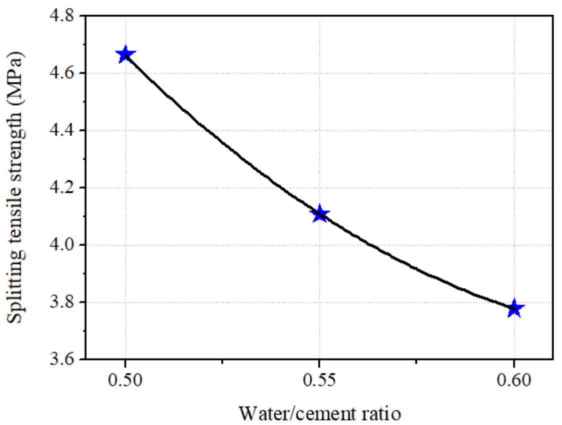


***Figure 12.*** *Change in the splitting tensile strength with the water/cement ratio*

## 5. Conclusions

The conclusions of the present study are summarized below:

- It is seen that the maximum compactness can be achieved with the granulometry curve of the aggregate type used in the present study. In this respect, it can be said that the aggregates in question can be safely used in concrete production.

- When the surfaces of the tested samples are examined, it can be clearly seen that there is not much damage, wear, and disintegration in the said aggregates. Thus, it can be said that the type of aggregate used is resistant.

- It was seen that there was not much change in the test results of the concrete samples prepared for the fixed parameters, i.e. the margin of error was low.

- A linear correlation and a good correlation ($R^2$=0.92) were determined between the splitting tensile strength and compressive strength of all concrete samples tested.

- In the present experimental study, when the related graphs are examined, it is understood that there is an inverse proportion between the compressive strength and water/cement ratio and the concrete mixtures are completely compressed. In this respect, it can be said that the results of the present study are in accordance with the literature.

- In this study, it was concluded that the natural aggregates obtained from river beds, which are expected to be particularly resistant, can be used in order to produce better quality and low-cost concrete.

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