The Investigation into the Effect of Hydrostatic Pressure on the Engineering Properties of Hardened Concrete

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Abstract

The aim of this study is to investigate the effect of hydrostatic pressure on the engineering properties of hardened concrete. To this end, a concrete column with dimensions of 100 cm width, 25 cm depth and 250 cm height was produced using C20 class concrete. While pouring the concrete, 15 cm reference cube samples were taken from the fresh concrete. After 28 days, 8 from the cube samples and 128 from different hydrostatic heights, in total 136 pieces of core samples with Ø100 mm diameter were taken and their compressive strength was determined. The average compressive strength of the reference core samples was 36.95 N/mm² and the compressive strength of other samples changed between 37.3 N/mm² and 43.0 N/mm² according to the hydrostatic pressure. It was concluded that compressive strength changed between 0.95% and 16.37% according to the reference sample. Statistical analysis was conducted based on the experimental results. The compressive strength of the core samples related to its hydrostatic height and physical properties were predicted with a high reliability. A model equation was formed to convert the compressive strength of the core samples into reference compressive strength according to hydrostatic height and the convertibility coefficients were ascertained.

Keywords: concrete; hydrostatic pressure; core sample; compressive strength

1. Introduction

Due to the plastic consistency and viscosity of concrete, hydrostatic pressure in structural elements such as columns and reinforced walls emerges. Over the years, various factors, which affect the lateral pressure of fresh concrete on vertical forms, have been investigated. These factors include rate of placing the concrete, temperature of the concrete, proportion of the concrete mix, consistency of the concrete, consolidation method of the concrete, impact during placing, size and shape of the formwork, amount and distribution of the reinforcing steel, unit weight of the concrete, hydrostatic height of the concrete, ambient temperature, smoothness and permeability of the formwork, pore water pressure and type of cement¹ and ². During placing, the material indeed behaves as a fluid but, if it is cast slowly enough or if it is at rest, it builds up an internal structure and has the ability to withstand the load from the concrete cast above it without increasing the lateral stress against the formwork. This conclusion was drawn by observing the decrease in pressure in the first few hours after casting even though the hydration process had not yet started³ and ⁴, the lateral stress on the formwork steadily decreased. The only phenomenon that can occur after casting at this time in fresh concrete is the build-up of the internal structure at rest⁵ and ⁶. As concrete hardens, the hydrostatic pressure decreases. Thus, the formwork can be removed after the concrete hardens. However, it must be taken into consideration that in hardened concrete, hydrostatic pressure affects the compressive strength of the concrete.

This situation is especially significant in preparing the reinforcement projects for buildings that are damaged by earthquakes. On the other hand, in situations where fresh samples of concrete are not taken, fresh concrete pressure test results are not compatible with the standards, or compressive strength is doubtful, it is crucial to determine the compressive strength of the concrete⁷. A common way of determining the in-situ strength of concrete is to drill and test cores⁸, ⁹, ¹⁰, ¹¹, ¹², ¹³, ¹⁴, ¹⁵, ¹⁶, and ¹⁷. Although the method consists of expensive and time-consuming operations, cores give reliable and useful results since they are mechanically tested on destruction¹⁸. However,
the test results should be carefully interpreted because core strengths are affected by a number of factors such as diameter, l/d ratio, and moisture conditions of the core specimen, the direction of drilling, presence of reinforcement steel bars in the specimen, and even the strength level of the concrete. In core samples, some mechanical and physical properties such as the compressive strength of the concrete, density, water absorption capacity, split tensile strength, expansion due to alkali-silica reaction, the space ratio, and saturation degree can be determined as well. The studies including the future standards related to this subject were published in several countries such as England, America and Turkey.

In the present study, the effect of hydrostatic pressure on the compressive strength of concrete was investigated. With this aim in mind, using C20 class concrete, a concrete column was produced. By taking samples from different hydrostatic heights of the column, the compressive strength was determined. In order to predict the compressive strength according to hydrostatic height and the physical properties of the samples, statistical analyses were conducted and prediction models were established.

2. Material and Method
2.1 Material
2.1.1 Formworks
In this study, 100 x 25 cm cross-sections and 250 cm high column formwork was produced. While producing the block, a 3 cm wide metal framed wooden panel with 50 x 100 x 2.5 cm dimensions was used on the front and back surfaces. 25 x 250 x 2.5 cm pine timber was used on the sides after this process and sika concentrated block liquid was applied on the interior surfaces of the block so the formwork would be prepared for pouring the concrete.

2.1.2 Concrete
In this study, a column block in a cross-section with 100 x 25 cm and 250 cm height was produced. While producing the block, a metal-framed wooden panel and pine timber were used on the sides. C20 ready mixed concrete was poured into the formwork to prevent segregation.

2.1.3 Casting, Curing, and Instrumentation of the Columns
The specimens were cast vertically in a specially fabricated stand and concrete was compacted in layers. During the casting of columns, concrete was poured vertically—similar to the direction of loading. The concrete was vibrated using a portable poker vibrator with a diameter of 3 cm and was manually poured. Control specimens in the form of cubes were also cast for concrete. The samples and control specimens were remolded after 24 hours and cured in a curing tank for 28 days. Then, the core samples were cured at room temperature until testing. The details of concrete mixtures including water to cement ratio (W/C) are presented in Table 1. The concrete properties of the columns are also presented in Table 1.

During this process, in order to use as a reference, 8 cube samples measuring 15 cm in dimension were taken according to Turkish Standards TS EN 12350-1 and were kept in a curing tank for 28 days.

2.2 Method
2.2.1 Taking Core Samples
Three days after pouring the concrete, the formwork was removed. A wet cure was applied for 28 days in the morning, in the afternoon, and in the evening to the construction site. After 28 days of pouring the concrete, in order to take the core sample, the position of the column was changed from vertical to horizontal. 16 in accordance with the column height and 8 by the width; a total of 128 core samples were taken. The internal diameter of the core samples was chosen as 100 mm and since the length of the samples was 25 cm, h/d=1.5 was chosen and a total of 128 core samples were taken. The core samples were taken similarly with the previous 8 pieces of the 15 cm cube reference ones (Fig.1.).

2.2.2 Determination of the Physical Properties of the Samples
All the samples taken were kept in the laboratory for 48 hours and their air-dry weights were measured with

| Class of the concrete | C 20/25 | Dmax: 22 | Consistency: 8.3 | Water/Cement: 0.63 | Weighted quantity |
|-----------------------|---------|-----------|------------------|---------------------|-------------------|
| Aggregates            | Amount  | The goal of the prescription | Moisture content % | The goal of the system | Total             |
| 0-5K                  | 546 kg  | 2.730 kg  | 5,6              | 2.880 kg            | 2.861 kg          |
| 15-25                 | 470 kg  | 2.350 kg  | 1,0              | 2.372 kg            | 2.251 kg          |
| 5-15                  | 486 kg  | 2.430 kg  | 1,0              | 2.452kg             | 2.417 kg          |
| Stone dust            | 347 kg  | 1.735 kg  | 5,5              | 1.828 kg            | 1.851 kg          |
|                      | 9.245 kg| 288 kg    |                  | 9.532 kg            | 9.380 kg          |
| CEM2 42.5R            | 290 kg  | 1.450 kg  |                  | 1.450 kg            | 1.448 kg          |
| Super plasticizers   | 2.32 kg | 11.6 kg   |                  | 11.6 kg             | 11.497 kg         |
| Water                 | 183 kg  | 915 kg    |                  | 626 kg              | 623 kg            |
|                      | 2.377 kg| 2.088 kg  |                  |                     | 2.082 kg          |
| 2.324 kg             | Unit Weight (for each m²) | 2.293 kg | 11.462 kg         |                     |
0.1 gr sensitivity. Afterward, these samples were kept in 20 ±2°C water until their weight became constant and saturated with water. Water saturated weights and their weights in water were measured. Samples were kept in a drying oven at 105 ±2°C until their weights were constant.

2.2.3 Determination of the Compressive Strength of the Samples

In order to conduct the compressive strength test, headings with 70% sulphur and 30% graphite were produced. Samples were kept in the laboratory setting for 24 hours and a compressive strength test was conducted according to TS EN 12390-4. As a result of the tests, samples were broken in accordance with TS EN 12390-3. The physical properties and compressive strength values of reference samples and others are provided in Table 2.

3. Analysis of the Findings

The descriptive statistics of the experiment results in a total of 128 core samples were conducted. The correlation coefficient between the fundamental physical properties, the height of hydrostatic pressure, and the compressive strength of core samples was determined. Multi-Linear Regression analysis (MLR) was carried out to predict the compressive strength of core samples. Variance analysis was conducted in order to test the significance of the model.

| Core row numbers for core samples on the column | Natural unit volume weight gr/cm³ | Unit volume weight for dry air gr/cm³ | Saturated unit volume weight gr/cm³ | Amount of water absorption % | Volume of voids cm³ | Hydrostatic height cm | Compressive strength N/mm² |
|-----------------------------------------------|----------------------------------|--------------------------------------|------------------------------------|-----------------------------|---------------------|------------------------|---------------------------|
| 1                                            | 2.552                            | 2.486                                | 2.574                              | 3.514                       | 8.030               | 235                    | 37.30                     |
| 2                                            | 2.596                            | 2.512                                | 2.618                              | 4.151                       | 9.365               | 224                    | 38.40                     |
| 3                                            | 2.550                            | 2.489                                | 2.570                              | 3.245                       | 7.437               | 213                    | 37.70                     |
| 4                                            | 2.899                            | 2.541                                | 2.655                              | 4.491                       | 10.213              | 191                    | 38.60                     |
| 5                                            | 2.808                            | 2.513                                | 2.608                              | 3.760                       | 8.595               | 180                    | 39.80                     |
| 6                                            | 2.590                            | 2.517                                | 2.614                              | 3.830                       | 8.744               | 147                    | 40.20                     |
| 7                                            | 2.604                            | 2.524                                | 2.625                              | 3.979                       | 9.092               | 136                    | 39.60                     |
| 8                                            | 2.606                            | 2.528                                | 2.627                              | 3.890                       | 8.912               | 114                    | 41.00                     |
| 9                                            | 2.635                            | 2.545                                | 2.658                              | 4.409                       | 10.000              | 103                    | 40.80                     |
| 10                                           | 2.585                            | 2.516                                | 2.606                              | 3.582                       | 8.229               | 92                     | 39.90                     |
| 11                                           | 2.573                            | 2.505                                | 2.594                              | 3.546                       | 8.151               | 70                     | 40.30                     |
| 12                                           | 2.587                            | 2.516                                | 2.609                              | 3.662                       | 8.386               | 59                     | 41.00                     |
| 13                                           | 2.538                            | 2.491                                | 2.557                              | 2.648                       | 6.177               | 48                     | 42.00                     |
| 14                                           | 2.573                            | 2.512                                | 2.592                              | 3.179                       | 7.379               | 35                     | 41.90                     |
| 15                                           | 2.554                            | 2.500                                | 2.573                              | 2.892                       | 6.717               | 23                     | 42.50                     |
| 16                                           | 2.547                            | 2.493                                | 2.566                              | 2.893                       | 6.713               | 11                     | 43.00                     |
| Reference                                     | 2.322                            | 2.343                                | 2.368                              | 1.074                       | 2.518               | -                      | 36.95                     |
3.1 Descriptive Statistics
The physical properties and descriptive statistics values of core samples for compressive strength are shown in Table 3.

3.2 Correlation Analysis
In order to determine the level of significance in the relationship between fundamental physical properties, hydrostatic height, and compressive strength of core samples, correlation analysis was carried out (Table 4.).

3.3 Multiple Linear Regression Analysis
In order to predict the compressive strength of samples according to the physical properties and the hydrostatic height, multiple linear regression analysis was carried out on all data and also only according to the hydrostatic height (Table 5.).

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### Table 3. Descriptive Statistics

| Properties investigated | N   | Range  | Min.   | Max.   | Mean  | Std. Error | Std. Deviation | Variance |
|-------------------------|-----|--------|--------|--------|-------|------------|----------------|----------|
| Compressive strength    | 16  | 5.70   | 37.30  | 43.00  | 40.235| .393       | 1.620          | 2.625    |
| Natural unit volume weight | 16  | .36    | 2.54   | 2.90   | 2.609 | .023       | .097           | .009     |
| Dry unit volume weight  | 16  | .06    | 2.49   | 2.54   | 2.510 | .004       | .018           | .000     |
| Saturated unit volume weight | 16  | .10    | 2.56   | 2.66   | 2.601 | .007       | .030           | .001     |
| Water absorption percentage | 16  | 1.84   | 2.65   | 4.49   | 3.592 | .126       | .519           | .270     |
| Volume of voids         | 16  | 4.03   | 6.18   | 10.21  | 8.229 | .274       | 1.129          | 1.274    |
| Hydrostatic height      | 16  | 224.0  | 15.0   | 239.0  | 127.47| 18.186     | 74.983         | 5623.0   |

### Table 4. Correlation Analyses

| Correlation coefficients | Compressive strength | Natural unit volume weight | Dry unit volume weight | Saturated unit volume weight | Water absorption percentage | Volume of voids | Hydrostatic height |
|--------------------------|----------------------|----------------------------|------------------------|-----------------------------|-----------------------------|----------------|-------------------|
| Compressive strength     | 1.00                 | - .273                     | .001                   | -.219                       | -.504                       | -.491          | .916              |
| Natural unit volume weight | - .273              | 1.00                       | .605                   | .638                        | .621                        | .628           | -.327             |
| Dry unit volume weight   | .001                 | .605                       | 1.00                   | .966                        | .813                        | .825           | .020              |
| Saturated unit volume weight | -.219               | .638                       | .966                   | 1.00                        | .935                        | .942           | -.211             |
| Water absorption percentage | -.504               | .621                       | .813                   | .935                        | 1.00                        | 1.00           | -.508             |
| Volume of voids          | -.491                | .628                       | .825                   | .942                        | 1.00                        | 1.00           | -.492             |
| Hydrostatic height       | .916                 | - .327                     | .020                   | -.211                       | -.508                       | -.492          | 1.00              |

### Table 5. Model Summary

| R       | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics |
|---------|----------|-------------------|-----------------------------|-------------------|
| .932    | .869     | .809              | .707                        |                   |

| R Square Change | F Change | df1 | df2 | Sig. F Change |
|-----------------|----------|-----|-----|---------------|
| .869            | 14.597   | 5   | 11  | .000          |

### Table 6. ANOVA\(^a\) Resolution

| Sum of Squares | df | Mean Square | F      | Sig. |
|----------------|----|-------------|--------|------|
| Regression     | 36.498     | 5   | 7.300 | .000 |
| Residual       | 5.501     | 11  | .500  |      |
| Total          | 41.999     | 16  |       |      |

### Table 7. Coefficients Resolution

| Model                  | Unstandardized Coefficients | Standardized Coefficients | Sig. | 95% Confidence Interval for B |
|------------------------|-----------------------------|---------------------------|------|-----------------------------|
| B                      | Std. Error                  | Beta                      | .574 | -258.719 - 150.839         |
| Natural unit volume weight (x1) | 1.764           | .275                      | .105 | -4.299 - 7.827              |
| Unit volume weight for dry air (x2) | 39.078          | 40.641                    | .430 | -50.373 - 128.529          |
| Amount of the water absorption (x3) | 24.817          | 20.108                    | .796 | -19.440 - 69.074           |
| Volume of voids (x4) | -12.146          | 9.428                     | -.846 | -32.896 - 8.604            |
| Hydrostatic height (x5) | .018            | .006                      | .820 | .013 - .005                 |

### Table 8. ANOVA\(^b\) Resolution

| Sum of Squares | df | Mean Square | F      | Sig. |
|----------------|----|-------------|--------|------|
| Regression     | 36.498 | 5   | 7.300 | .000 |
| Residual       | 5.501 | 11  | .500  |      |
| Total          | 41.999 | 16  |       |      |

### Table 9. Coefficients Resolution

| Model                  | Coefficients |
|------------------------|--------------|
| B                      | Std. Error   |
| Natural unit volume weight (x1) | 1.764           | .275                      |
| Unit volume weight for dry air (x2) | 39.078          | 40.641                    |
| Amount of the water absorption (x3) | 24.817          | 20.108                    |
| Volume of voids (x4) | -12.146          | 9.428                     |
| Hydrostatic height (x5) | .018            | .006                      |

a. Predictors: (Constant), Natural unit volume weight (x1), Unit volume weight for dry air (x2), Amount of water absorption (x3), Volume of voids (x4), Hydrostatic height (x5).

b. Dependent Variable: Compressive strength (y).
3.3.1 Physical Properties and Regression Analysis According to the Hydrostatic Height

In order to predict the compressive strength of samples according to the physical properties and the hydrostatic height, multiple regression analysis was carried out. The results of the analysis can be seen below (Table 6. and Table 7.).

The model equation is shown below. According to this:

\[ y = -53.94 + 1.764x_1 + 39.078x_2 + 24.817x_3 - 12.146x_4 + 0.018x_5 \]

In the equation;
- \( y \): Compressive strength (N/mm\(^2\))
- \( x_1 \): Natural unit volume weight,
- \( x_2 \): Dry unit volume weight,
- \( x_3 \): Percentage of water absorption
- \( x_4 \): Volume of voids
- \( x_5 \): Hydrostatic height

The relationship between the estimated and real compressive strength according to the physical properties [Natural unit volume weight (\(x_1\)), Dry unit volume weight (\(x_2\)), Percentage of water absorption (\(x_3\)), Space volume (\(x_4\)), Hydrostatic height (\(x_5\))] and compressive strength of core samples with multiple linear regression can be seen in Fig.2.

![Fig.2. The Relationship between Estimated Compressive Strength and Experimental Compressive Strength](image)

![Descriptive Statistics](image)

|                | Mean   | Std. Deviation | N  |
|----------------|--------|---------------|----|
| Compressive strength | 40.2500 | 1.67212       | 16 |
| Hydrostatic height  | 117.56  | 74.49829      | 16 |

![Model Summary](image)

|                | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics |
|----------------|----------|-------------------|-----------------------------|-------------------|
| R              | .943     | .888              | .888                        | df1 = 14, Sig. F = .000 |

3.3.2 Regression Analysis According to Hydrostatic Height

Regression analysis was conducted and a prediction model was established to predict the compressive strength of core samples according to hydrostatic height. The model obtained from the regression analysis, which aims to predict the compressive strength related to hydrostatic height specifically, can be seen in Fig.3. By using this model, different core compressive strength values taken from different hydrostatic heights can be converted into core values taken from reference samples using the coefficients in Table 8.

![Fig.3. The Estimated Compressive Strength Value According to the Hydrostatic Height](image)
• The coefficient between the compressive strength and the natural unit volume weight and the compressive strength of hardened concrete can be useful.

Table 8. The Coefficients of Converting the Compressive Strength of the Core Samples According to Hydrostatic Height

| Upper border distance (cm) | Coefficient for converting to reference values |
|---------------------------|-----------------------------------------------|
| 0                         | 1.00 (reference value)                         |
| 15                        | 0.98                                           |
| 26                        | 0.97                                           |
| 37                        | 0.97                                           |
| 50                        | 0.96                                           |
| 59                        | 0.95                                           |
| 70                        | 0.95                                           |
| 100                       | 0.93                                           |
| 103                       | 0.93                                           |
| 114                       | 0.93                                           |
| 136                       | 0.92                                           |
| 147                       | 0.91                                           |
| 150                       | 0.91                                           |
| 158                       | 0.91                                           |
| 180                       | 0.90                                           |
| 191                       | 0.89                                           |
| 200                       | 0.89                                           |
| 202                       | 0.89                                           |
| 215                       | 0.88                                           |
| 227                       | 0.87                                           |
| 235                       | 0.87                                           |
| 239                       | 0.87                                           |

4. Results and Discussion

In this study, the effect of hydrostatic height in hardened concrete on the compressive strength was investigated experimentally and statistically. The results are indicated below.

• The average compressive strength of the reference samples was 36.95 N/mm² and the compressive strength of other samples changed between 37.3 N/mm² and 43.0 N/mm².

• The compressive strength of the concrete increased when the hydrostatic height increased as well. This increase ratio according to the reference sample was 0.95% for 0.15 m, 4.22% for 0.5 m, 7.09% for 1.0 m, 9.95% for 2 m, 12.82% for 2.35 m, and 16.37% for 2.39 m.

• It was determined that the natural unit volume weight of core samples changed between 2.54 gr/cm³ and 2.90 gr/cm³, dry volume unit weight between 2.49 gr/cm³ and 2.54 gr/cm³, water saturated unit volume weight between 2.56 gr/cm³ and 2.66 gr/cm³, absorption amount between 2.65 and 4.49, and volume of voids between 6.18 cm³ and 10.21 cm³.

• The coefficient between the compressive strength and saturated unit volume weight of the core sample was -0.273 and measured at 0.01 for dry unit volume weight, 0.219 for saturated unit volume weight, -0.504 for water absorption amount, -0.491 for the volume of voids, and 0.916 for hydrostatic height. According to this finding, the relationship between hydrostatic height and compressive strength is quite strong, on the other hand, the relationship between compressive strength, water absorption amount, and volume of voids is nearly the same or at mid-level but negative. The relationship between dry unit volume weight and the compressive strength of the concrete is not significant.

• Core samples are generally taken from the buildings that would be reinforced to determine the compressive strength of the concrete. However, in this study, it was seen that the compressive strength of the core samples changed between 0.95% and 16.37%, according to hydrostatic height. For this reason, the compressive strength of the core samples can be used if they are converted into reference compressive strength according to the suggested coefficient below (Table 5.). In order to convert the compressive strength of the concrete into a reference value, the hydrostatic height must be measured while taking the core samples.

• Besides, for different hydrostatic height values not included in the table, the model equation obtained from regression analysis can be used to predict the compressive strength of the core samples related to hydrostatic height.

• The model equation obtained through multiple linear regression analysis can be used to predict the compressive strength related to the hydrostatic height and physical properties of the core samples (R²=0.932).

In the case of using a different concrete class, mixture design, and different types and amounts of plasticizers, investigating the effects of hydrostatic height in structural elements such as columns and reinforced walls on the compressive strength of hardened concrete can be useful.

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