Variation of In-Place Concrete Core Strength in Structures from Istanbul Area: Statistical Analysis of Concrete Core Data

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Abstract: The research has been undertaken to determine the strength and quality of concrete material used to build various types of structures in various localities in the city of Istanbul, located within the first-degree disastrous area for a potential earthquake risk. Concrete core samples collected from a total of 244 structures (buildings, industrial, and governmental structures), for which the construction details, such as the production type (cast in place and/or ready mixed) and class of concrete material are known, have been tested for their compressive strength. Statistical analyses of the collected data show that the tested core samples have equivalent specified strength of between 1.61 and 70.05 N/mm². The mean value for a total of 1,892 characteristic strength values has been found to be 22.01 N/mm² with a standard deviation value of 9.99 N/mm². The statistical results obtained using the production type and class (C14, C16, C18, C20, C25, and C30) of concrete indicate that the strength quality of both cast-in-place and ready-mixed concrete is, in general, quite far away from meeting the required concrete strength. Although ready-mixed concrete gives better values, the results show that approximately 42% of all the analyzed structures are below the quality required to build the structures safely.

DOI: 10.1061/(ASCE)0899-1561(2004)16:5(507)

CE Database subject headings: Turkey; Compressive strength; Concrete; Earthquakes; Structural safety.

Introduction

The research undertaken after the major earthquake occurred in Turkey in August 1999 showed that one of the most devastating causes of this earthquake was the extent of damage occurred in reinforced concrete structures. The purpose of this paper is to present the procedure and results of the statistical analyses of in situ tests for determining in-place concrete strength of random structures from a first-degree dangerous area for a potential earthquake risk using concrete core samples. For this purpose, core specimens were obtained from various types of structures to determine concrete compressive strength of structures. The main objective of analyzing the compressive strength of core samples is to document in-place strength information, which has been rationally accounted for in the assessment of the safety of an existing structure.

Methodology

Sampling Strategy

The core samples have been drilled at random locations throughout the structures in an effort to obtain an overall compressive strength value for each structure examined. Sullivan (1991) proposed that it would be sufficient to take four cores to assess concrete in-place strength statistically, while Bartlett and MacGregor (1999) recommended that a minimum of six samples would be required for the same procedure. ASTM C83 (1983) “Standard practice for examination and sampling of hardened concrete in constructions,” on the other hand, mentions that the number of core samples taken from each category of concrete should be not less than five. In this work, as an optimized approximation, only the structures from which five or more samples are available were considered for assessment of strength of structure.

Statistical Tests

The statistical analyses for the collected core samples have been carried out using the equivalent specified concrete strength values and the samples were classified using their production type and class. Calculations were made using the statistical methods given in ASTM C42-90 (1990), ASTM E178-80 (1980), and Bartlett and MacGregor (1999).

The development of the procedure for converting the core strengths into equivalent in place strengths is described in Bartlett and MacGregor (1999). The conversion equation is:
where \( f_{c,\text{ip}} \) = equivalent in-place strength; and \( f_c \) = core strength. Strength correction factors \( F_{1/d} \) and \( F_{\text{dia}} \) account for the effect of the length-to-diameter of the core, and \( F_r \) accounts for the effect of any reinforcing bars oriented at right angles to the core axis. These factors equal 1.0 if the core is 100 mm (4 in.) in diameter, has a length-to-diameter ratio of 2, and does not contain reinforcing bars. Strength correction factors \( F_{\text{mc}} \) and \( F_d \) account for the core moisture condition and the strength loss due to damage induced by drilling.

Detection of Outliers

Outlying observations, that can be described as values deviated significantly from the generally observed trend within a data set, are always possible due to imperfect drilling, handling, or testing procedures. In order to obtain an accurate compressive strength estimate for a range of concrete core tests, all spurious values need to be detected and removed from the data set. In this study, detecting and purging the spurious values have been made using statistical criteria given in ASTM E178-80 (1980), “Standard practice for dealing with outlying observations.” In the proposed method, the doubtful value is recommended to be included in the determination of the sample statistics.

Calculation of Characteristic Strength Values

Calculation of characteristic strength values from a data set requires the data to have been converted to equivalent in-place strengths and any spurious values to be removed. For a large population of members from different structures, the variability of the average in-place strength between structures dominates the overall variability of the in-place strength. It is therefore appropriate to use core strength data from a particular structure to estimate the average in-place strength. To obtain characteristic strength value, the lower limit of the 90\% (one-sided) confidence interval on the average in-place strength \( (\bar{f}_{c,\text{ip}})^{0.90} \) should be calculated from

\[
(\bar{f}_{c,\text{ip}})^{0.90} = \bar{f}_{c,\text{ip}} - 1.28 \times \sqrt{\frac{(k_1 s_{c,\text{ip}})^2}{n} + (\bar{f}_{1/d})^2 V_{1/d}^2 + (\bar{f}_{\text{dia}})^2 V_{\text{dia}}^2 + (\bar{f}_r)^2 V_r^2 + (\bar{f}_{\text{mc}})^2 V_{\text{mc}}^2 + (\bar{f}_d)^2 V_d^2}
\]

where \( f_{c,\text{ip}} \) and \( s_{c,\text{ip}} \) = sample mean and the sample standard deviation of the equivalent in-place strengths. \( k_1 \) = ratio of the 90th percentile of the student \( t \) distribution with \( (n-1) \) degrees of freedom to the 90th percentile of the standard normal distribution. Values of \( k_1 \) are selected depending on the number of cores taken from a structure. The variables \( V_{1/d}, V_{\text{dia}}, V_r, V_{\text{mc}}, \) and \( V_d \) are coefficients of variation associated with strength correction factors as described in Bartlett and MacGregor (1999).

The equivalent specified strength \( f'_{c,\text{eq}} \) is obtained from

\[
f'_{c,\text{eq}} = k_2 (\bar{f}_{c,\text{ip}})^{0.90}
\]

where values of \( k_2 \) = coefficient of variation due to variations of in-place strength throughout the structure, and depend on number of structures from which cores were taken, the number of batches, and the type of concrete production. An average value of 0.85 for \( k_2 \) was chosen here as the number of structures from which the tested cores was obtained varies significantly, and there are considerable batch-to-batch variations.

Evaluating the Data

The compressive strength values obtained from a total of 244 structures have been plotted on a histogram in Fig. 1. A normal distribution can be seen from the diagram indicating that the data can be statistically evaluated. Fig. 2 shows the overall distribution of the equivalent compressive strength values for all core samples collected from the structures. It can be seen from Fig. 2 that the data points are, in general, scattered widely. The mean value for the equivalent specified strength of all structures is found to be 15.55 N/mm\(^2\) with a standard deviation value of 6.83 N/mm\(^2\), and the maximum and minimum values of 41.86 N/mm\(^2\) and 3.33 N/mm\(^2\), respectively.

Three criteria have been used for evaluating the equivalent in-place compressive strength of concrete: (1) The concrete class; (2) concrete production type; and (3) concrete production type versus concrete class.

In the graphs of Fig. 2 prepared using these criteria, each data point corresponds to the equivalent specified compressive strength of concrete in a structure. Blank circles show the mean values for each series and the error bars are given as dark lines.
Concrete Class

Analyzing the data using the concrete class is aimed at addressing whether the analyzed structures have the concrete quality required for their project. A widely scattered distribution can be seen in Fig. 3. The results show that 101 structures out of 244 analyzed have compressive strength values less than that would be required for their projects. The data show that approximately 59% of the structures, for which the compressive strength has been assessed to be C14 in their project, have the compressive strength values lower than that required for C14 class strength. In Table 1, the results of all type of concrete classes for equivalent specified concrete strength are given.

Concrete Production Type

The strength quality of concrete in Istanbul structures differs significantly depending on the concrete production type. In order to document the effects of concrete production type statistically on the in-place concrete strength values of structures, analyzed core strengths from a total of 244 structures have systematically been

Table 1. Statistical Summary of the Classification of Concrete Class

<table>
<thead>
<tr>
<th>Concrete class</th>
<th>Average strength (N/mm²)</th>
<th>Standard deviation (N/mm²)</th>
<th>Maximum strength (N/mm²)</th>
<th>Minimum strength (N/mm²)</th>
<th>Number of structures</th>
<th>Unsatisfactory structure’s ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C14</td>
<td>13.56</td>
<td>3.530</td>
<td>22.26</td>
<td>4.18</td>
<td>103</td>
<td>59</td>
</tr>
<tr>
<td>C16</td>
<td>20.36</td>
<td>4.770</td>
<td>26.36</td>
<td>10.32</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>C18</td>
<td>22.51</td>
<td>7.270</td>
<td>50.39</td>
<td>9.87</td>
<td>103</td>
<td>29</td>
</tr>
<tr>
<td>C20</td>
<td>22.22</td>
<td>5.650</td>
<td>31.87</td>
<td>11.50</td>
<td>26</td>
<td>31</td>
</tr>
<tr>
<td>C25</td>
<td>34.54</td>
<td>3.830</td>
<td>38.27</td>
<td>29.50</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>244</td>
<td>41</td>
</tr>
</tbody>
</table>

Fig. 4. In-place strengths for different concrete production types

Table 2. Statistical Summary of the Classification of Concrete Production Type

<table>
<thead>
<tr>
<th>Production type of concrete</th>
<th>Average strength (N/mm²)</th>
<th>Standard deviation (N/mm²)</th>
<th>Maximum strength (N/mm²)</th>
<th>Minimum strength (N/mm²)</th>
<th>Number of structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-in-place</td>
<td>14.09</td>
<td>4.990</td>
<td>50.39</td>
<td>4.18</td>
<td>119</td>
</tr>
<tr>
<td>Ready-mixed</td>
<td>23.06</td>
<td>6.590</td>
<td>43.68</td>
<td>9.80</td>
<td>125</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>244</td>
</tr>
</tbody>
</table>

Table 3. Statistical Summary of the Classification of Concrete Class and Production Type

<table>
<thead>
<tr>
<th>Class and type</th>
<th>Average strength (N/mm²)</th>
<th>Standard deviation</th>
<th>Maximum strength (N/mm²)</th>
<th>Minimum strength (N/mm²)</th>
<th>Number of structures</th>
<th>Unsatisfactory structures (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-In-place concrete</td>
<td>C14</td>
<td>10.671</td>
<td>3.139</td>
<td>20.098</td>
<td>91</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>C16</td>
<td>7.609</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>C18</td>
<td>14.461</td>
<td>7.685</td>
<td>41.854</td>
<td>19</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ready-mixed concrete</td>
<td>C14</td>
<td>11.290</td>
<td>1.818</td>
<td>13.462</td>
<td>7</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>C16</td>
<td>19.712</td>
<td>3.557</td>
<td>23.785</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>C18</td>
<td>20.707</td>
<td>5.804</td>
<td>39.280</td>
<td>80</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>18.592</td>
<td>5.440</td>
<td>27.637</td>
<td>22</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>C25</td>
<td>29.860</td>
<td>3.099</td>
<td>33.464</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>229</td>
<td>61</td>
</tr>
</tbody>
</table>
compared with the concrete production type. The results shown in Fig. 4 and Table 2 indicate that the ready-mixed concrete has a mean value of 23.06 N/mm² for compressive strength, while cast-in-place concrete gives a much lower mean value of 14.09 N/mm².

**Combination of Concrete Class and Production Type**

In Table 3 and Fig. 5, the concrete class and production type have been combined to assess the equivalent strength of concrete more accurately and to classify the structures as individual sets. It can be seen from Table 3 that 87% of structures that were built using cast-in-place C14 concrete have compressive strength values lower than that of C14 concrete strength. Similarly, this ratio has been found to be 79% for the cast-in-place C18 concrete.

For ready-mixed concrete, the number of unsatisfactory structures is much less than those of cast-in-place concrete, but still 31% of C18 and 59% of C20 concrete have strength quality lower than that required. Ready-mixed C16 concrete has a much better strength value as it was produced by a single station for a high strength.

**Conclusions**

According to the Turkish standards, it is generally accepted that the equivalent compressive strength of concrete used to build concrete structures in potential areas for an earthquake risk should not be less than the strength of C25 concrete, and this strength quality (or greater strength) is normally preferred for first- and second-degree earthquake areas. In this study, concrete core samples were collected from Istanbul structures in a way that they would statistically represent the entire city located in a first-degree earthquake area. The results of the statistical analyses carried out on concrete core samples can be summarized as below.

- The tested cores from a total of 244 structures yield a mean equivalent compressive strength of 15.55 N/mm² (standard deviation of 6.83 N/mm²). The strength values vary significantly within a wide range with minimum and maximum values of 3.33 and 41.86 N/mm².
- Large variations in compressive strength values have been found even in the same structure (up to 400% for some buildings) indicating that batch-to-batch variation during construction is an important factor.
- Statistical results obtained using the concrete class show that remarkable portions of C14 (59%) and C20 (31%) concrete have unsatisfactory values of compressive strength. As a result of the statistical analyses of the collected data, approximately 42% of all the analyzed structures (n=244) have been found to have a compressive strength lower than the required strength.
- It has been documented that ready-mixed concrete has, in most cases, greater compressive strength compared to cast-in-place concrete, although the strength quality of both classes is usually lower than the required strength.

**Notation**

The following symbols are used in this technical note:

- \( F_d \) = strength correction factor due to damage sustained during drilling;
- \( F_{dia} \) = strength correction factor for diameter;
- \( F_{mc} \) = strength correction factor for core moisture condition;
- \( F_r \) = strength correction factor for core containing reinforcing bars;
- \( F_{1/td} \) = strength correction factor for core length-to-diameter ratio;
- \( f_c \) = compressive strength of a concrete core strength;
- \( f_{c,ip} \) = equivalent in-place strength;
- \( f_{c,eq} \) = equivalent specified strength;
- \( k_1,k_2 \) = constants;
- \( s_{c,ip} \) = sample standard deviation of the in-place strengths;
- \( V_d \) = coefficient of variation of strength correction factor \( F_d \);
- \( V_{dia} \) = coefficient of variation of strength correction factor \( F_{dia} \);
- \( V_{mc} \) = coefficient of variation of strength correction factor \( F_{mc} \);
- \( V_r \) = coefficient of variation of strength correction factor \( F_r \); and
- \( V_{1/td} \) = coefficient of variation of strength correction factor \( F_{1/td} \).

**References**


