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Statistical distributions of in situ microcore concrete strength

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ABSTRACT

Quality control processes require accurate knowledge of in situ compressive strength of concrete. The most widely accepted method of determining the compressive strength of concrete in existing structures is to test core specimens drilled from hardened concrete. The strength level is an appropriate criterion because it is a decisive factor in determining the quality of concrete, and in addition, other most significant properties of the concrete can be related to its compressive strength. According to the widely accepted international standards and recommendations, the minimum core diameter is generally fixed at 100 mm. However, drilling such rather large size cores may prove hazardous in many cases. In this regard, estimation of concrete strength in structures may be gained from compression tests conducted on cores having a diameter considerably less than the recommended one of 100 mm. As it is not always safe to drill cores of 100 mm, utilizing smaller diameters is more practical. Microcores can be drilled in situ with very light equipment, resulting in greatly reduced costs and less damage to the structure. The statistical characteristics of microcores on the other hand are not understood completely.

This paper examines the results of the in situ compressive strength tests applied on 28 mm diameter microcores drilled from the columns and shear walls of various structures. A total number of 264 cores drilled from 11 different structures were tested. The equivalent compressive strength values of 28 mm diameter cores were evaluated by using statistical methods. The distributions suitable for the data were determined. The distribution of the data did not exhibit a unique shape. We found that the distributions which best characterize the 28 mm diameter cores for buildings 1 and 2 were Johnson S_B and log-normal distributions. These two relatively new buildings also yielded higher mean equivalent compressive strengths compared to the microcores taken from other buildings. The log-normal probability density function (for buildings 1 and 2) was derived only as a function of the coefficient of variation of concrete strength, for dimensionless compressive strength values of microcores. For other buildings (3–11), Johnson S_B distribution was found to be more appropriate. These findings were verified through goodness of fit tests.

1. Introduction

Compressive strength, which is the most important concrete parameter, depends on a number of factors: type and proportion of ingredients, strength level, position of concrete in a structure, type and size of the structure, compactness, curing and age [1]. Concrete quality control is usually performed during construction by testing standard specimens (cubes or cylinders) made from the same batch that is used in the construction. There are, however many objections to this procedure due to the variations in the factors listed above between laboratory and in situ conditions. The results from the standard specimen tests might not represent the actual strength of concrete in a structure [1]. The estimation of in situ concrete strength is one of the most important problems when it is necessary to assess the bearing capacity of a structure [2]. Core testing is one of the widely accepted methods for assessing in situ strengths [3]. Although this method is an expensive and time consuming procedure, according to many researchers, it is reliable and it gives useful results since the cores are mechanically tested to destruction [4].

The strength level of the concrete in the structure should be determined on the basis of results obtained from tests on cores drilled from the structure. The strength level is an appropriate criterion, because it is a decisive factor in determining the quality and actual strength of the concrete [5]. In order to estimate the quality of the concrete accurately, it is generally required to drill a relatively large number of core cylinders [5]. Where the core is to be used for compression testing, British and American standards require that the core diameter is at least three times the nominal maximum aggregate size. It is recommended that a minimum diameter of 100 mm should be used according to the international

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standards. However, core diameter smaller than 100 mm (as low as 50 mm) is permitted when the core is intended to be used for determination of in situ strength of concrete [6]. Since it is not always possible to drill cores of this size, researchers and practitioners are often forced to utilize 28 mm diameter cores (microcores). Microcores also offer many advantages in terms of reduced cutting effort, and time with the use of very lightweight equipment. What is more important, by using this technique is that damage to the structure becomes virtually negligible and core testing can be classified as a non-destructive method. In this respect, microcore testing brings together the advantages of classical core tests and those offered by non-destructive methods. In microcore testing, the in situ evaluation of average concrete strength is obtained directly from an analysis of the results of compression tests performed on the concrete being considered [2,7]. However, a disadvantage of microcores is the lack of statistical results concerning microcore compressive strength distributions. The factors which affect the results of normal cores may also be expected to influence microcores [8].

1.1. Statistical nature of microcores

The actual strength of concrete in the structure is a random variable which is affected by many factors such as the age of the concrete, the compaction quality, curing, and the size and type of the load-bearing member from which the core is drilled [9]. Concrete cores are different from moulded specimens because their surfaces may be damaged (such as microcracking caused by drilling) during drilling. Drilling also cuts through aggregate particles, which may pop-out during testing since they are not wholly contained within the concrete matrix. If the affected zone has a constant thickness irrespective of the core diameter, the larger the core diameter, the greater the damage [9]. Microcores themselves are also more prone to being damaged during drilling, handling and storing. Therefore, in practice, in situ strength variations are unavoidable [9]. The frequency distribution of such random data is a major factor determining the type of statistical analysis that can be validly carried out on any data set [10].

In stochastic modeling of a random variable, it may be necessary to recreate the variability through fitting a sufficiently flexible theoretical probability distribution to observed data. It is desired to represent this variability through probability distributions of sufficient flexibility. There are two methods to achieve this. These are: using the observed data to define an empirical distribution, and fitting a theoretical distribution to the histogram of the observed data [11]. The latter is preferable as it allows analyzing the system for situations outside the norm. This is essential when carrying out an experimental analysis [11]. In this study, we followed this procedure. Details about the theoretical distributions will be given in Section 3. Note that the bin size of the histograms used in this study to be compared against the theoretical distributions was optimized according to the methods proposed by Shimazaki and Shinomoto [12].

Skewed distributions are particularly common when mean values are low and variances are high. In addition, values cannot be negative. Such skewed distributions often closely fit the log-normal distribution [10]. Log-normal distributions are usually characterized in terms of the log-transformed variable, using as parameters the expected value, or mean, of its distribution, and the standard deviation. This characterization can be advantageous as, by definition, log-normal distributions are symmetrical again at the log level [10,13]. The log-normal distribution has been used in a wide range of engineering applications. A random variable x is said to be log-normally distributed if $\log(x)$ is normally distributed. The distribution is skewed to the left [10].

Another skewed distribution, one in the Johnson system, is often called the S_B distribution, indicating it as the bounded member of this family [14,15]. The S_B distribution introduced by Johnson in 1949, if not as much as log-normal distribution, has also been used widely in many applications. Johnson's definition and parameterization of the S_B distribution is based on normality transformation [14,16].

It is essential in modeling applications concerning the in situ concrete strength that the selected distribution to model the collected data truly reflects the properties of the data. Nevertheless, it is of concern that there is a lack of literature aimed at determining the probability distributions of in situ concrete strength deemed appropriate for use in the construction activities [11].

There are many theoretical distribution functions which could fit a set of data, and because of this, a measure of the goodness of fit between the theoretical function and the data is necessary. One of these methods is the visual assessment where the probability density function (PDF) plot is placed on top of the plot of the input data histogram. To undertake a visual assessment of the goodness of fit, the shape of each PDF should be compared with the shape of the histogram. The PDF that has the closest matching shape should be selected and used to represent the input data in any further analysis. Abourizk et al. [17] suggested that the visual assessment of the fit is often superior compared to other methods. However, visual assessment is subjective and susceptible to potential human error. Therefore, quantification of the level of the match is necessary and can improve confidence significantly in the selection of PDF. Two well known statistical tests (hypothesis tests) provide such mathematical support: Kolmogorov–Smirnov (K–S) and Anderson–Darling (A–D) tests among others [11,17].

A concept known as the p-value provides a convenient basis for drawing conclusions in hypothesis testing applications [18]. The p-value approach in decision-making is convenient because nearly all computer softwares that provide hypothesis-testing computation print out p-values along with values of the appropriate test statistic. A p-value is the lowest level (of significance) at which the observed value of the test statistic is significant [13].

1.2. Aim of the study

The goal of this study is to determine and verify the distribution of in situ microcore strength. In this experimental investigation, the in situ compressive strengths of 28 mm diameter microcores were investigated. The equivalent compressive strength values of 28 mm diameter cores drilled from columns and shear walls of 11 different buildings were evaluated using statistical methods. The distributions suitable for the data were determined.

2. Experimental study

In this experimental study, 28 mm diameter microcores were drilled from various members such as columns and shear walls of different buildings and the properties of in situ concrete were investigated. In order to estimate the quality of the concrete, large number of microcores was drilled. The concrete type was ready-mixed concrete in both buildings.

In a discussion written by Lewis and Bowman in 1980, it was demonstrated that with small-diameter cores for an estimate of the strength of the concrete mass, they should be taken near the centre of that mass [19,20]. In another study carried out by Bartlett and MacGregor in 1994, cores were drilled from the middle of most columns, walls, and large blocks, where the strength is assumed to be reasonably uniform. Strength of cores from the top and bottom of the short column specimens tested by Haque et al., in 1991 were averaged to determine the strength in the middle [9,21]. In the present experimental study, the microcores were taken near the centre of members such as columns and shear walls. The microcores were drilled in the basement of buildings. The columns and shear walls are coded and the corresponding numbers of microcore samples tested are as shown in Table 1.

The specified concrete strength (28 days), f'_c of building 1 was 20 MPa. The specified concrete strength, f'_c of other 10 buildings was 18 MPa. The 28 mm diameter microcores had l/d ratios between 1.0 and 2.0 according to the procedures