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Quality Control and the Safety of Structural Concrete Buildings (pp. 113-123)

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Abstract

Various aspects of quality control were examined as they affect the safety of structural concrete buildings. The study was based essentially on broad review of a wide range of literature, especially the findings of published research works. The investigation highlighted those processes which affect the quality of concrete and reinforcing steel to include concrete batching and mixing, formwork design and construction, concrete placing, compaction and curing, as well as the control testing of concrete and reinforcing steel. It noted that since the strength of a structure is a random variable, it is necessary to exercise good quality control on the various aspects of concrete work which affect that parameter in order to minimize its variability. This in turn, the paper concluded, will ensure that the structural performance of the finished building sensibly conforms to the design intentions.

Keywords: Quality Control, Structural Safety, Concrete, Reinforcing Steel, Control Testing.

Introduction

A building is structurally safe if it has a safety margin greater than zero, according to the following expression:

Safety Margin = Strength of Structure – Load on Structure > 0 (1)

From the above expression, it is clear that the safety margin will be greater than zero if the strength of the structure is greater than the load acting on it. When the safety margin is less than zero, the result is failure. Unfortunately safety margin is a random variable because both the strength of a structure and the load on it are random variables. The precise form of the probability density functions for strength and load are not known, hence the form of the function for safety margin is also unknown. However a rational approach to structural safety can offer some help. One such approach leads to the following requirement for structural safety:

$$\gamma_s \text{ x Mean Strength} \geq \gamma_L \text{ x Mean Load} \qquad (2)$$

where γ_s = partial safety coefficient less than unity, applied to the mean strength;

γ_L= partial safety coefficient greater than unity, applied to the mean load.

The magnitude of each partial safety coefficient depends on the variability of the quantity to which it applies (mean strength or mean load), and on the chosen value of the reliability index of the structure. The value of the reliability index is usually established by calibration against well-proved and established designs (Nilson, Darwin and Dolan, 2004).

Usually if the strength of the structure is known and the load on it is also known, it is a simple matter to ensure the safety of the structure by providing a safety margin greater than zero. In practice, the process of doing this is considerably more involved than it may appear. This is because as noted earlier, both strength and load are random variables. This study is concerned with the various measures which need to be put in place to ensure that the variance of structural strength is minimal. To achieve this objective, it is necessary to examine the various factors influencing the strength of a structure.

The strength of a structure depends on the strength of the materials from which it is composed. Minimum material strengths are specified in standardized ways. Actual material strengths are not precisely known and are therefore random variables. In addition to the strength of constituent materials, the strength of a structure also depends on the level of care exercised in making a structure. This level of care on the other hand, is a reflection of the quality of supervision and inspection of works at construction stage, i.e., quality control. Therein lies the connection between structural safety and quality control.

The load-bearing frames of structural concrete buildings consist of concrete, reinforced with steel bars. Structural concrete is arguably the most widespread structural material today. It is indeed difficult to imagine any modern city without a preponderance of structural concrete buildings. A number of reasons account for this. It offers greater flexibility in choice of structural form than other structural materials, and modern methods of structural analysis, powered by the possibilities presented by computers permit the engineer to analyze these complex structures with some confidence. This confidence is backed up by well documented data on the performance of reinforced concrete structures, resulting from research on concrete, as a material, and on the behaviour of structural models.

Although major advances have been made over the years in the methods of production of concrete, understanding of the performance of concrete structures, design philosophy, and improved mechanization and mechanical handling, nevertheless, failure of reinforced concrete structures still occurs. In his concluding commentary on the lessons from past structural failures, Bate (1983) noted that failures are very seldom due to any lack of basic scientific or technical knowledge, but rather to a failure to ensure that the knowledge was properly applied, or to an absence of engineering judgement. Furthermore, he continued, failures are usually due to human error, which are likely to be the result of mismanagement, i.e., the acceptance of the wrong priorities, misunderstanding or lack of communication between those with different responsibilities within the project. A recent spate of building collapse failures in Nigeria has attracted several investigations into the reasons for structural failure. Such investigations include those of Dare (2001), Salau (2005), Arum and Babatola (2006), and Arum (2008), among several others. Among the various identified causes of building failure, those that touch on the poor quality of materials, laxity in works supervision, poor construction practices, and employment of unqualified personnel, inadequate maintenance and unprofessional conduct, were more frequently cited. Most of these causes can be grouped into one, namely, poor quality control. This is because by definition, quality control is the supervision exercised on site to ensure compliance with minimum standards of material and workmanship, in order to ensure the performance of the structure according to the design. It also usually includes the control testing of the quality of material to ensure that it conforms to the design requirements and, where it deviates significantly from this, the taking of necessary corrective action (Jackson, 1981).

In view of the foregoing discussion, the aim of this work is to review the various controls which must be exercised in the production, placement and curing of concrete, as well as the control testing of concrete and steel reinforcing bars to ensure that a concrete building performs according to its design.

Quality Control of Concrete

The design of concrete structures is based on the assumption of certain properties of concrete such as strength, but the actual strength of the concrete produced, whether on site or in the laboratory, is a variable quantity (Neville and Brooks, 1987). The sources of variability are many: variations in mix ingredients, changes in concrete making and placing process, contractor's variability, poorly skilled workmen, unprofessional conduct by team members, and also with respect to test results, the variations in the sampling procedure and variations in the actual testing itself. It is important to minimize this variability by quality control measures and by adopting the standard testing procedures.

The purpose of quality control of concrete is to measure and control the variation of those operations which affect the strength or the uniformity of concrete: batching, mixing, formwork design and construction, placing, compaction, curing, and testing. According to Falade (2000), a good quality concrete can be obtained by effectively controlling both human and non-human factors. According to this source, human factor refers to effective supervision and good workmanship while non-human factor refers to the materials used in concrete production.

In the production of concrete, quality control should be exercised in the type and amount of cement to use. The different types of cement used in Nigeria are assumed to comply with the requirements of the relevant Standard (BSI, 1989). In addition, this Standard specifies a lower limit of 250kg/m^3 and an upper limit of 550kg/m^3 to the cement content in concrete. It is also a well known fact that bagged cement sold in the market which is assumed to weigh 50kg sometimes weighs as little as 45kg or less after having been re-bagged by some greedy cement dealers for profit maximization. Since 45kg cannot effectively replace 50kg of cement in concrete work, good supervision is required to arrest such dangerous substitution. In addition, good construction practice favours the use of cement from the same source for any particular project in order to reduce variation in the quality of concrete. Cement should be used in the order in which it is delivered to site and lumpy cement should be discarded.

There should be quality control in the type, size (Arum and Alhassan, 2006), grading, and purity or cleanness (Arum and Udoh, 2005) of the aggregates to be used. Research works (Raheem and Aderounmu, 2002; Arum and Alhassan, 2006) have shown that aggregate with nominal maximum size of 25mm makes concrete of maximum compressive strength. The research by Arum and Udoh (2005) showed that aggregate with 30% by mass of particles smaller than 0.075mm reduced the strength of concrete by as much as 52%. In addition, it was noted in the said work that materials such as coal and lumps of clay should not be allowed in aggregates for concrete because they are capable of softening and forming weak pockets. The water/cement ratio of a concrete mix should also be controlled. The strength of concrete depends very much upon the hydration reaction. Water/cement ratio is indeed the single most important factor that influences the strength of concrete (Kong and Evans, 1987). In general, the less the quantity of water used in the production of concrete, the greater the strength of concrete. The hydration reaction consumes a specific amount of water. Concrete is usually mixed with more water than needed for hydration. The extra water is needed to give concrete sufficient workability. Low water-to-cement ratio leads to high strength but low workability while high water-to-cement ratio leads to low strength but high workability. Control should therefore be exercised in the amount of mixing water used and the method of compaction employed. Adequate supervision should ensure that the concrete is workable enough to be thoroughly compacted by whatever means that is available, but without requiring excessive water content to achieve that workability.

Effective supervision is also required to ensure that the batching of concrete is correctly done and the constituents proportioned as required. Batching is specified to be done by weight but in most cases the large volume of concrete work necessitates batching by volume using head pans, wheelbarrows and other such containers. In these cases effective supervision is especially necessary to ensure correct proportioning of the constituents. Also mechanical mixing should be favoured over manual mixing and where it must be done manually, adequate monitoring must be exercised.

Quality control should also be exercised in aggregate grading. It is advisable to use single-size aggregates, store them separately, and batch them separately into the mixer. By combining single-size aggregates at the mixer or plant, greater accuracy and control can be obtained compared with the use of a graded aggregate. Regular grading tests should be carried out on sands delivered to site to ensure that no significant shift occurs. It should also be ensured that only specified curing methods are used for the concrete as method of curing can also affect the strength of concrete.

Since strength is a variable quantity, when designing a concrete mix, the aim should be to obtain a mean strength higher than the minimum required from the structural point of view so that every part of the structure can be expected to be made of concrete of adequate strength. The usefulness of quality control of concrete production is not only in the compliance with specifications but also in reduction of production cost for the concrete producer. For example, poor quality control will result in a higher standard deviation, and therefore a higher mean strength will need to be obtained according to the following formula:

$$f_m = f_{\min} + KS \tag{3}$$

where $f_m =$ mean strength;

$f_{\min} =$ minimum strength (or characteristic strength);

$K =$ probability factor (also known as the acceptability index);

$S =$ standard deviation.

This higher mean strength will have to be achieved by using more cement in order to obtain the specified characteristic strength.

The quality of hardened concrete can be assessed in the laboratory through the determination of its compressive strength by crushing standard concrete cubes in accordance with the provisions of the relevant Standard (BSI, 1983).

Control Testing of Steel Reinforcing Bars

The strength of reinforcing steel is less variable than that of concrete mainly because steel is a homogeneous material and it is mill-produced; its quality is assured by the producer who must exercise systematic quality controls, usually specified by pertinent standards. The foregoing statement generally applies. In Nigeria as in many other non steel-producing countries however, the reality is different. In the work by Arum (2008), it was shown that use of sub-standard reinforcing steel in structural concrete works was a very likely major contributor to a recent high incidence of building collapse in Nigeria. The work gave a clear insight into how low strength mild steel bars were often used in works for which high-yield ribbed bars were actually specified. This was possible due to laxity on the part of the supervising personnel (often unqualified) who sometimes dispensed with the necessity to subject steel bars supplied to construction sites to tensile testing, even when such bars had neither markings on their bodies to indicate their producer mills, nor had product certificates to show their structural properties.

For such bars, their structural properties should be verified before they are used for structural concrete. Such properties include their tensile strength, yield strength (or proof stress) and percentage elongation. These properties should be verified by subjecting appropriate samples of the bars to tensile test in accordance with relevant standards. For instance, in accordance with the provisions of the International Organization for Standardization for ribbed bars ISO 6935-2 (1991), fifteen (15) or sixty (60) test pieces must be taken from each test unit and subjected to tensile test. According to this Standard, for properties which are specified as characteristic values, the following parameters shall be determined:

a) all individual values, x_i, of the 15 test pieces $(n=15)$;
b) the mean value, m_{15} (for $n=15$);
c) the standard deviation, s_{15} (for $n=15$).

Each test unit is considered to correspond to the requirements if for all properties the following condition is fulfilled:

$$m_{15}-2.33s_{15}\geq f_k \qquad (4)$$

where f_k = the required characteristic value;

2.33 = the value for the acceptability index, k, for $n=15$ for a failure rate of 5%.

If the condition stated above is not fulfilled, the index

$$k'=\frac{m_{15}-f_k}{s_{15}} \qquad (5)$$

is determined from the test results available. Where $k'\geq 2$, testing can be continued. In this case forty five (45) further test pieces should be taken and tested from different bars in the test unit, so that a total of 60 test results are available ($n=60$).

The test unit shall be considered to comply with the requirements if the condition stated below is fulfilled for all properties:

$$m_{60}-1.93\times s_{60}>f_k \qquad (6)$$

where 1.93 is the value for the acceptability index, k, for $n=60$, for a failure rate of 5%.

Conclusion

The following conclusions derive from this investigation:

- The strength of a structural concrete building is a random variable which depends not only on the strengths of concrete and its reinforcing steel, which also are random variables, but also on the quality of supervision and inspection of works at construction stage.

- The variability of the strength of a structure can be minimized by exercising adequate quality control on the materials from which the structure is constructed. Those materials in the case of structural concrete buildings include concrete and reinforcing steel.
- Effective quality control ensures conformance of constructed structure with design intentions, which in turn guarantees structural safety.

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