EARLY AGE STRIKING OF FORMWORK TO GGBS CONCRETES: A PROPOSED DECISION MAKING TOOL

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Abstract
Strength testing of standard cured cubes does not give an accurate representation of early age in-situ strength. Such test results may particularly underestimate early age insitu strength of concrete made with GGBS. This adversely affects site practice through adherence to potentially pessimistic formwork striking times. This paper presents a proposed methodology to enable a contractor make an optimal determination of striking time for repetitive elements in a project, with particular relevance to GGBS concretes. Once a reliable methodology to evaluate in-situ strength is initially verified the decision process to strike formwork can be simplified in follow-on pours of similar concrete elements. A project-specific test program for early age strength determination is reduced to a primarily desktop exercise using standard cube strength data, a relationship between initial testing and the application of a maturity method.

Keywords: (GGBS, early age strength, formwork striking)

1. Formwork striking of GGBS concrete

Irrespective of binder type, BS 8110 (1985) set out the minimum in-situ strength to be reached before striking concrete members as:

- 5 N/mm^2 for members in compression to protect against possible frost damage
- 10 N/mm^2 or twice the stress a member is subjected to for a member in flexure to withstand a load.

The early age strength development of concrete is influenced by the binder composition. Clear (1994) found that the higher the proportion of GGBS the slower the early age strength development of the concrete. This was concluded from an experiment designed to assess the formwork striking time of concretes with high levels of GGBS. This work illustrated the slower early age strength development of concretes containing high replacement levels of GGBS but also demonstrated that temperature matched curing (TMC) gives a more accurate measure of the early strength of in-situ concrete than cubes cured at 20^{o}C. Soutsos et al (2005) found that estimation of insitu early age strengths of concrete made with supplementary cementitious materials could be underestimated by standard cube curing regimes.

Standard cured cubes do not take all the factors that contribute to the strength development of concrete into account. As a result they do not give the most accurate representation of the in-situ strength. Sometimes they overestimate the strength, while at other times they underestimate the strength. Compressive strength testing of cubes that are temperature match cured gives the best representation of in-situ strength of concrete. However, as temperature matched curing is only representative of a single point within a concrete element, carefully consideration must be given to the position within an element to which the TMC bath is referenced.

Harrison (1995) presented tables of the recommended time to elapse before striking formwork for a specified grade of concrete, given the mean air temperature and cement type. These tables are valid for CEM I's of strength class 42.5 and 52.5 but do not consider GGBS concretes.

This paper proposes a decision-making tool for striking time based on strength and maturity criteria. The development of the decision-making flowchart outlined in this paper is based on data and experience generated in a study by the authors (Reddy and Richardson, 2008) of early age strength measurements and predictions of CEM II(A-L)/GGBS concretes. The flowchart allows for a systematic assessment and prediction of in-situ strength so that an efficient, yet safe, decision can be made on the striking of formwork in GGBS concrete elements, potentially at earlier ages than specified times based on standard specifications. This is achieved through the development of a relationship between initial testing and the application of a maturity method. The maturity method is then used to accurately predict the in-situ strength of GGBS concretes. Once a reliable methodology to evaluate in-situ strength is initially verified the decision process to strike formwork can be simplified in follow-on pours of concrete elements. This methodology can permit the reduction of a test program for early age strengths throughout a project to a primarily desktop exercise using established standard cube data and a maturity method. This speeds up construction through reduced formwork turnaround times.

2. Maturity methods and temperature models

The strength development of concrete is dependent on the rate of hydration, which itself is dependent on the reaction temperature. Concrete strength can therefore be expressed as a function of time and temperature - the maturity function (Neville, 2002). A maturity method may be used to estimate the in-situ concrete strength at a point in a concrete element if the following four steps are achieved:

- Obtain a strength development curve for a mix at a standard temperature of 20°C
- Measure or calculate the actual temperature-time history
- Determine a 'maturity index' using the temperature-time history
- Estimate in-situ strength using the strength development curve and the maturity index

Maturity functions have been are expressed in units of centigrade hours (°Ch) or in terms of 'equivalent age'. Weaver and Sadgrove (1971) put forward the principle of Equivalent Age for Portland cements while others (Wimpenny & Ellis, 1991, and Clear, 1994) verified the principle of Equivalent Age for a range of combinations of GGBS and Portland cement. The principle of Equivalent Age is that concrete cured for a period Δt at a average temperature of θ°C has an Equivalent Age T_{eq} to a concrete cured at 20°C. It is calculated by Equation 1:

$$T_{eq} = \sum \left(\frac{\theta + 16}{36} \right)^2 \times \Delta t \qquad (1)$$

Harrison (1995) developed a software package to model the temperature rise in concrete. The model can be used in conjunction with maturity functions to predict the in-situ strength of concrete. The model produces temperature rise curves for concretes made with CEM I or CEM I and an addition. Increasingly in Ireland there is interest in data for a combination of CEM II(A-L) and GGBS. The applicability of Harrison's model was investigated using a CEM II(A-L) and GGBS binder (Reddy and Richardson, 2008) and this study further investigated the applicability of the principle of Equivalent Age to concrete made with combinations of CEM II(A-L) and GGBS binder. The findings were used in the development of the decision-making tool for striking of formwork set out in Section 4.

3. Experimental verification of principles underlying the proposed methodology

The development of the flowchart for the striking of formwork, presented in this paper, was underpinned by an experimental programme on limestone cement / ggbs concretes, which is reported in more detail in another paper (Reddy and Richardson, 2008). The experimental programme was designed to investigate the early age strength of GGBS concretes to assist in the development of the decision-making process. The binder content was 350 kg/m^3 and was a combination of CEM II(A-L) and GGBS at replacement levels of 30%, 50% and 70%. The experiment was conducted on the site of Kilsaran Concrete, Clonee, Co. Meath. This ensured that the source of concrete and laboratory facilities were in close proximity, providing a controlled workspace. Three large concrete elements were cast. The elements were 350mm thick.

A desktop exercise was completed using the CIRIA Temperature Prediction Model to generate the probable temperature curves for the different GGBS replacement levels in the elements cast. The temperature model indicated temperatures in excess of 20^{o}C, suggesting that higher strengths would be measured using temperature matched cured strength measurement rather than standard cured cubes.

A suite of 100 x 100 x 100 mm cubes was cast with each element cast and the cubes were cured at a standard temperature of 20^{o}C. Cubes were prepared and crushed in accordance with the European Standard 12390-2 and 12390-3.

A variety of in-situ strength assessment methods were used and assessed during the study. These were temperature matched curing, the LOK test and the principle of 'Equivalent Age' maturity method. Various maturity functions were available and a literature review indicated that the appropriate maturity function for estimating the in-situ strengths of GGBS concretes is the principle of 'Equivalent Age' put forward by Weaver and Sadgrove (1971). The 'Equivalent Age' models employed both measured in-situ temperatures and predicted ones.

The strength criterion set out in BS 8110 for members in flexure was used in this study (10 N/mm^2 or twice the stress a member is subjected to). Based on this criterion and a target of striking formwork at an age of 2 days, Table 1 indicates which methodology gave a positive or a negative decision in respect of readiness for striking at age two days based on the measured or estimated strength meeting the requirement of 10 N/mm^2.

Table 1 - Summary of decision outcome using different methodologies for striking formwork at 2 days using a particular CEM II (A-L)/ ggbs concrete mix (Reddy and Richardson, 2008)

Description of binder type	**Methodology used to measure or predict in-situ strength**				
	Strength test (20°C Cube)	**Strength test (TMC Cube)**	**Equivalent Age (Insitu temperatures)**	**Equivalent Age (Modelled temperatures)**	**LOK Test**
CEMII (A-L) / 30% GGBS	✓	✓	✓	✓	✓
CEMII (A-L) / 50% GGBS	✓	✓	✓	✓	✓
CEMII (A-L) / 70% GGBS	✗	✗	✗	✗	✗

The findings summarised in Table 1 indicate that at a concrete age of two days all methodologies gave a '*YES'* decision to strike at 30% and 50% GGBS replacement levels and a '*NO*' decision to strike at a 70% GGBS replacement level. Based on the experience gained in the experimental work a decision-making model was designed that could enhance fast track construction in GGBS concretes. This is presented in Section 4.

4. Proposed Decision-making Flowchart for Striking of Formwork

4.1 Flowchart and overview of process

The proposed flowchart is presented in Figure 1 with subsections in Figure 2 and 3. The main steps in the flowchart are:

- Determine suitability of project
- Determination of striking criterion to be applied
- Initial Testing
- Verify relationship between maturity estimates and initial test results
- Application of maturity method to subsequent similar concrete elements

4.2 Explanation of steps in the process

The steps in the flowchart are explained in the subsections that follow.

Suitability of project

The flowchart is to be used where many similar elements are being cast throughout a project, and can be grouped into elements of the same type, dimensions and concrete mix. An example is a multi-storey structure where the same slab design (dimensions, detailing, mix specification) is being used on many or all floors. The flowchart could also be applied to other groups of elements in such a structure, including columns, beams or walls. If the project is not suitable then use the standard criteria for striking formwork as per specification for each element as it is cast.

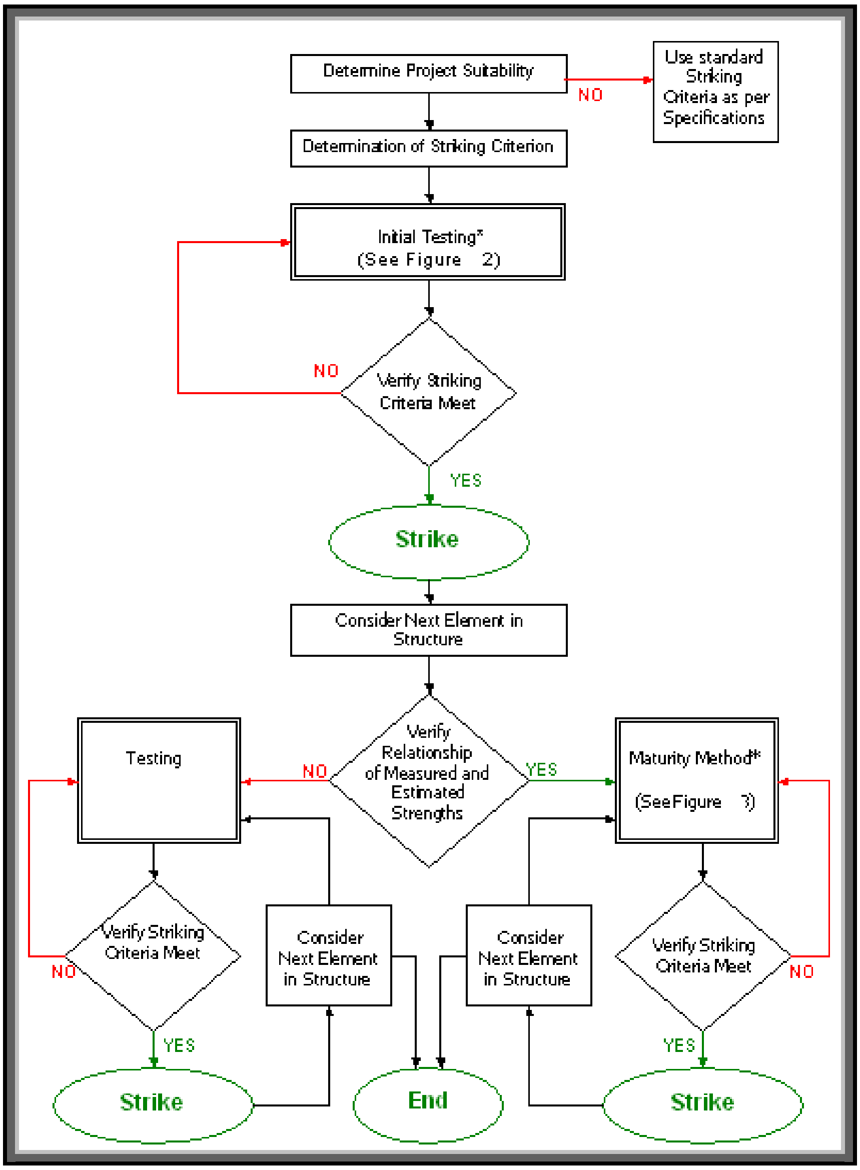

Figure 1 – Decision-Making Flowchart for the Striking of Formwork

Striking criterion

Determine the striking criterion in the form of the minimum strength, for the grouped elements in question. This can be found in the relevant standards or may come as an instruction from the specifier, taking account of the particular circumstances of the project.

Initial testing

An initial test programme is required to determine data on measured strength and equivalent age estimated strength. This process requires the steps indicated in Figure 2.

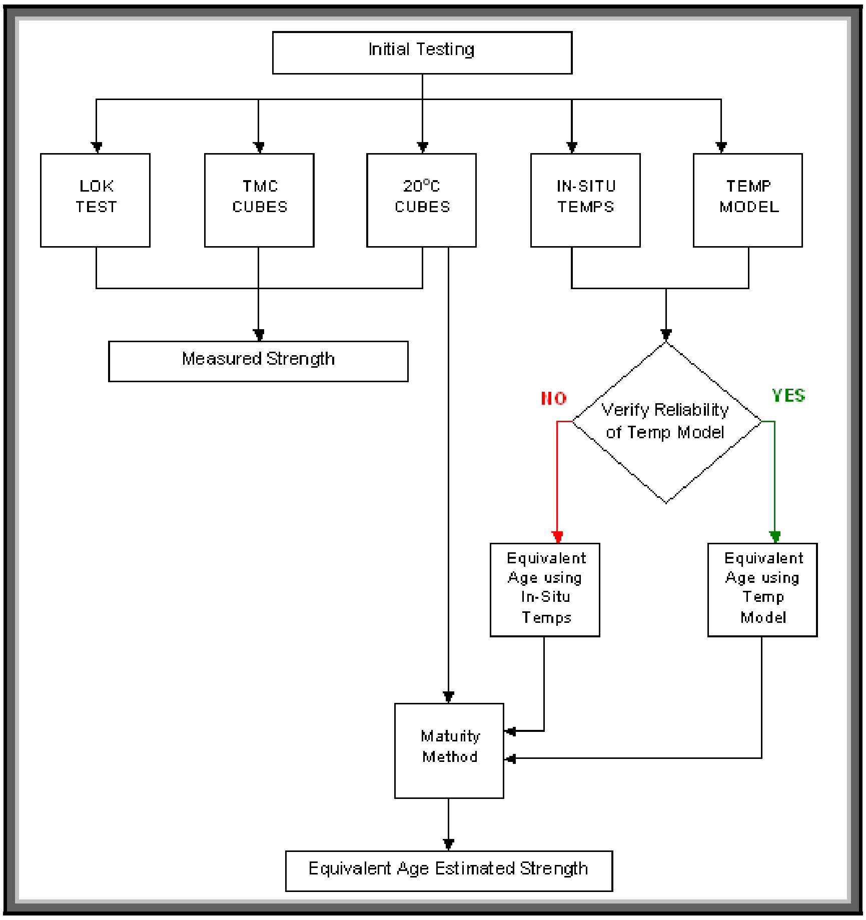

Figure 2 – Initial Testing Programme, Sub Chart of Figure 1

The steps in the initial testing programme are as follows:

- Conduct temperature matched curing ('TMC Cubes') and standard cube testing ('20°C Cubes') for the element being considered to obtain a measured strength.
- A non-destructive in-situ strength assessment method, such as the LOK test, may also be used if desired to obtain a measured strength.
- In parallel to the cube testing, record in-situ temperatures and generate a temperature-time curve using the CIRIA temperature model.
- Verify the reliability of the modelled temperature-time curve compared to the in-situ temperature-time curve.
- If there is a good correlation between the in-situ and modelled curves then the model can be used to accurately generate future temperature-time curves for subsequent elements.
- If there is not a good correlation, disregard the temperature model and continue to record in-situ temperatures on subsequent elements to determine the temperature-time curve.
- Apply a maturity method based on the principle of Equivalent Age to determine the maturity index/equivalent age. Use either the temperature-time curve from the in-situ temperatures or the temperature model, depending on the outcome of the previous steps.

- Use the Equivalent Age and the strength development curve at 20°C to give an equivalent age estimated strength.

Verify if the measured strengths obtained from initial testing meet the criterion for striking formwork. If yes, strike the formwork and apply the principle to the next element in the element group. If no, continue with initial testing until the criterion has been reached and then strike the formwork. The next element in the element group can then be considered.

Verification of relationship between maturity estimates and initial test results
Verify the relationship of measured and estimated strengths obtained from initial testing. To establish this relationship, the Equivalent Age estimated strength must be greater than or equal to the TMC measured strength when the TMC measured strength meets the striking criterion.

Application of maturity method to subsequent similar concrete elements
If the relationship has been verified, the maturity method illustrated in Figure 3 can be used to accurately predict the in-situ strength of subsequent elements of the same type that are cast throughout a project.

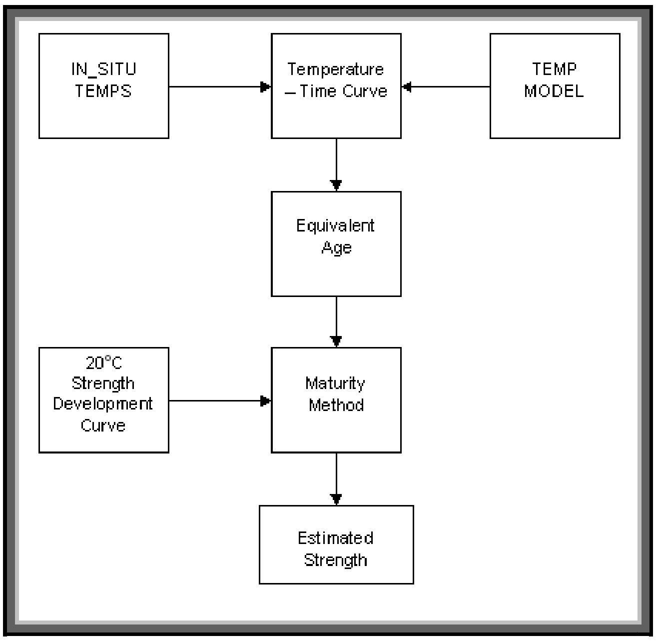

Figure 3 – Maturity Method flowchart, Sub Chart of Figure 1

The steps in the maturity method flowchart are as follows:
- The temperature-time curve may be generated using the CIRIA model or recorded in-situ temperatures depending on the results obtained during initial testing.
- Use the temperature-time curve to determine the maturity index/equivalent age. (The strength development curve at 20°C has been determined previously during initial testing and further cube testing is no longer required).
- Use the Equivalent Age maturity method and the strength development curve at 20°C to give an estimated strength.

If the relationship has not been verified, the maturity method will not accurately predict the in-situ strength and further testing should be conducted to measure the in-situ strength of subsequent elements of the same type that are cast throughout a project.

4. Conclusions

The optimal striking of formwork when using CEM II(A-L)/GGBS concrete requires reliable early age strength estimates. The methodology outlined in this paper allows this and is based on investing resources in data determination specific to one concrete mix at one point in one element. Its benefit is where the data determined can be further utilised throughout a project and therefore its application is particularly relevant to projects with significant repetition of element type. For example, once the relationship between the maturity function and TMC cube strength is established through detailed testing on one slab, then for subsequent slabs of the same mix and dimensions the maturity function alone can be used to predict in-situ strengths and determine if it is safe to strike formwork. If the CIRIA temperature model has been verified as matching the in-situ temperatures then this process can be further streamlined and reduced to a desktop exercise alone. At most, the required testing for the use of a verified maturity method is the recording of in-situ temperatures. Use of this decision-making flowchart can reduce the amount of testing required and can speed up construction throughout a project. The proposed decision-making flowchart (Figure 1) offers a methodology for determining the striking time for safe and efficient removal of formwork to GGBS concretes at the earliest possible age.

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