A STUDY OF MEASURED AND PREDICTED EARLY AGE IN-SITU STRENGTHS OF LIMESTONE CEMENT / GGBS CONCRETES

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Abstract
The early age strength of concrete influences project duration through its effect on the minimum striking time of formwork. Accurate assessment of early age strength is a prerequisite to making a decision for striking formwork at optimal timings, especially for GGBS concretes. Increasingly, limestone cement is becoming the dominant cement type in Irish concrete practice. This paper reports an investigation of the measured and predicted early age strength of CEM II (A-L)/GGBS concretes with replacement levels of 30%, 50% and 70% GGBS. Various methodologies were used including: strength testing of standard cured cubes and cubes subjected to temperature matched curing; LOK testing of in-situ specimens; and the application of maturity methods to predict strength through both measured and modelled temperatures. All methods proved consistent in respect of decision-making for striking of formwork based on strength criteria.

Keywords: (GGBS, early age strength, limestone cement)

1. Background to study

The experiment reported in this paper was designed to investigate the early age strength of GGBS concretes to assist in the development of a decision-making tool for the optimal striking of formwork. The early age strength development of GGBS concretes is slightly different to that of Portland cement-only concretes and this can affect site practice, such as the specification of minimum time to strike formwork. However, since the strength requirements for striking GGBS concretes are no different to Portland cement-only concretes, accurately assessing the early age strength of such concretes allows decision making on striking formwork at optimal timings. The temperature of concrete at early ages may be higher for in-situ pours, still in formwork, than for control specimens cured under standard conditions. Thus control specimens may underestimate the in-situ strength of GGBS concretes leading to longer than necessary striking times.

An experiment was designed to measure the early age strengths of concrete containing combinations of CEM II (A-L) with GGBS replacement levels of 30%, 50% and 70%. Early age strengths were measured using a variety of assessment methods and were used to determine if the minimum criterion for striking a suspended slab was reached after two days. The assessment of the methodologies used led to the development of a decision-making tool for the striking of formwork based on strengths and maturity criteria (Reddy and Richardson, 2008). This paper presents the findings of the experiment that provided inputs to the development of the decision-making tool.

2. Materials and methods

2.1 Materials

Three reinforced concrete panels, representing in-situ elements, and a suite of 100 x 100 x 100 mm cubes were cast, using three concrete mixes. The dimensions of the panels were 700 mm x 1800 mm x 350 mm. The formwork was removed after two days. A literature review did not provide a definitive guide to striking times for GGBS concretes and the decision to strike after two days was taken after consulting with contractors who are using GGBS in Ireland. The experiment was conducted on the site of Kilsaran Concrete, Clonee, Co. Meath. This ensured that the source of concrete, the in-situ specimens and laboratory testing facilities were in close proximity, providing a controlled workspace.

The mix used was a designed mix provided by Kilsaran Concrete. The binder content of 350 kg/m^3 was a combination of CEM II (A-L), strength class 42.5N, and GGBS at replacement levels of 30%, 50% and 70%. The aggregate comprised washed sand fine aggregate and crushed rock coarse aggregate. A plasticiser (P300) was used. Details of the mixes are presented in Table 1.

Table 1 – Mix design

Mix type	Mix composition per m^3								
	Cement (kg)	**ggbs (kg)**	**D20 (kg)**	**D10 (kg)**	**Sand (kg)**	**Dust (kg)**	**Water (litres)**	**Admixture (litres)**	**w/c**
30% GGBS	245	105	708	236	662	220	189	0.70	0.54
50% GGBS	175	175	708	236	662	220	189	0.70	0.54
70% GGBS	105	245	708	236	662	220	189	0.70	0.54

2.2 Methods

Standard cure cube strengths
A suite of 100 x 100 x 100 mm cubes was cast at the same time as each wall element and cured at the standard temperature of 20^{o}C. Three cubes were cast for testing per day of test and strength was determined at 2, 3, 4, 7, 14, 28 and 56 days. Cubes were prepared and crushed in accordance with the European Standard 12390-2 & 3.

Temperature-matched curing cube strengths
A suite of companion 100 x 100 x 100 cubes was cast concurrently to the casting of the standard cured cubes. Two cubes were cast for testing per day of test and strength was determined at 2, 3, 4, 7, 14, 28 and 56 days. These cubes were temperature matched cured in a TMC bath attached to thermocouples in the cover zone, mid height, of the panels cast. The cubes were wrapped in cling film, sealed with tape and placed into the TMC bath immediately after casting. The cubes were de-moulded after one day and placed back in the bath. Later on in the experiment, when the temperature in the panels had dropped to ambient

temperature, the cubes were removed from the TMC bath and stored in water in the concrete laboratory.

LOK strength test

The principle behind the LOK test method is that the force required to pull out an insert can be correlated to the concrete's compressive strength. The inserts used in this study were of the 'fixed to formwork' type. Each reported LOK test result is an average of four individual tests from the same region. Seven test ages were used in this study (2, 3, 4, 7, 14, 28 and 56 days). The inserts were fixed in seven columns of two inserts on each main face of the in-situ specimen, a total of 28 inserts per panel.

Predicted strength – maturity method

Predicted strengths were also investigated in the context of applying the findings of the research reported in this paper to the development of a decision-making tool for optimal striking of formwork to GGBS concretes. Various maturity functions have been derived to estimate the in-situ strength of concrete. Following a literature review the maturity function investigated in this study for estimating the in-situ strengths of GGBS concretes was based on the principle of Equivalent Age put forward by Weaver and Sadgrove (1971). The comparative effect of using a temperature-time history derived from a CIRIA temperature model and the recorded in-situ temperatures was investigated. The CIRIA prediction model developed by Harrison (1995) was used to generate the probable temperature curves for the different GGBS replacement levels in the panels cast. The surface temperature curve was used for initial estimates.

3. Results and discussion

3.1 Cube strengths

The cube strengths recorded for cubes cured under both curing regimes (standard and TMC) are presented in Figure 1, 2 and 3 for replacement levels of 30%, 50% and 70% respectively. The cube results at all replacement levels indicated the significance of actual temperature on strength development. Detectable differences between data derived from TMC cubes and the 20°C cured cubes was evident, with standard cured cube strengths tending to underestimate early in-situ strength and overestimate later in-situ strengths. The elements were cast during the winter months when ambient temperatures were low and this caused the reduction in strength of the TMC cubes compared to the standard cubes at later testing day ages. The ambient temperatures recorded during the experiment on the 70% GGBS replacement level element never exceeded 20°C for a significant period of time. The cube results illustrated in Figure 3 reflect this and show how the standard cubes can overestimate the in-situ strength of an element in cold conditions at a high level of GGBS replacement.

The minimum strength requirement for striking formwork may be determined from standards. A value of 10 N/mm^2 was the reference strength used in the decision-making tool, developed in the wider context of this study. A target striking time for the formwork was set at two days. The standard and TMC cube results indicated that both the 30% and 50% GGBS concretes met this early strength requirement by the target age. The cube results from the 70% GGBS replacement level element show that the required strength of 10 N/mm^2 was not reached after two days and that the formwork would have to remain in place for another day.

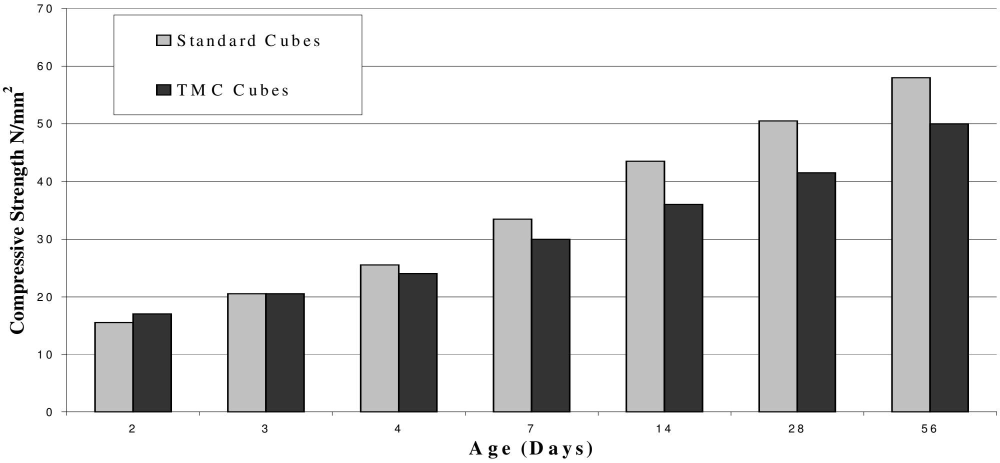

Figure 1 – Cube strengths for CEM II (A-L) / GGBS at 30% Replacement Level

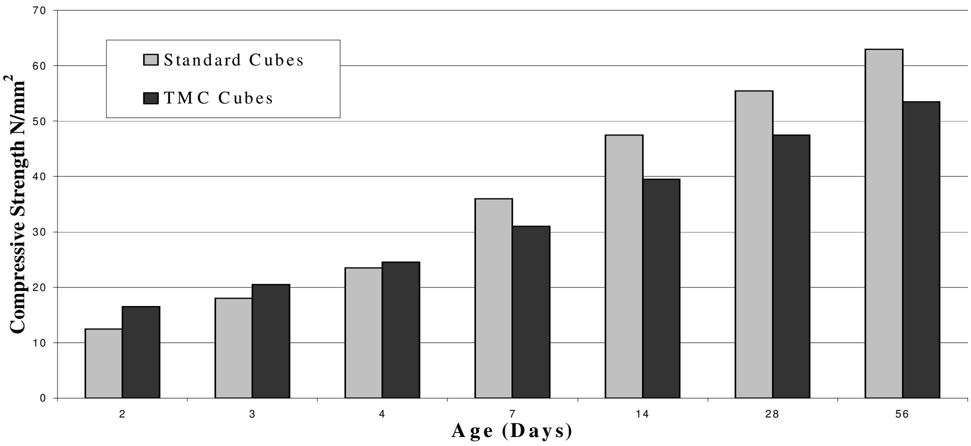

Figure 2 – Cube strengths for CEM II (A-L) / GGBS at 50% Replacement Level

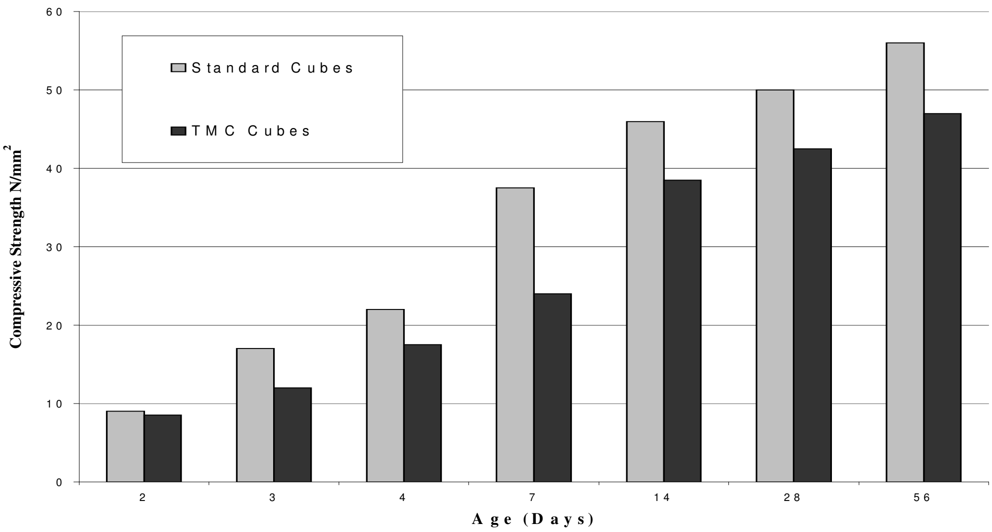

Figure 3 – Cube strengths for CEM II (A-L) / GGBS at 70% Replacement Level

3.2 LOK test results

The LOK tests results are presented in Table 2. The recorded values (kN) were averaged and converted into a N/mm^2 value using manufacturer's correlation tables.

Table 2 – Average LOK test result converted to a value in N/mm^2

Mix type	Converted LOK test average result for a specific age (N/mm^2)						
	2 days	**3 days**	**4 days**	**7 days**	**14 days**	**28 days**	**56 days**
30% GGBS	11.8	15.0	17.3	18.6	23.3	25.9	26.4
50% GGBS	13.8	15.5	18.6	23.1	25.3	32.0	38.0
70% GGBS	8.9	12.0	15.8	22.6	30.1	32.9	35.2

The trends obtained from the LOK tests correlated reasonably well with the TMC cube strengths at early day ages. The correlation diverged at later day ages. The results validated the formwork striking decision findings from the TMC cured cube strength results, in that the 30% and 50% GGBS replacement level elements were shown to have reached the requirement of 10 N/mm^2 after two days whereas this was not the case for the 70% GGBS replacement level.

3.3 Predicted strengths through application of maturity method

Early age in-situ strengths were predicted through application of a maturity function and the validity of these results were examined through comparison with the measured strength test results. Applicability of the maturity method to CEM II(A-L)/GGBS concrete included comparison of results from predictions of strength based on temperature-time histories that were recorded and that were modelled using the CIRIA Temperature Prediction Model. The temperature-time histories for the 30%, 50% and 70% GGBS replacement levels are presented in Figures 4, 5 and 6 respectively. These showed a reduction in the development of the heat of hydration with increased levels of GGBS due to its latent reaction.

The modelling of temperature-time histories indicated that the modelling was potentially applicable to CEM II(A-L)/GGBS concretes but divergence increased with higher replacement levels. As expected, higher replacement levels of GGBS resulted in lower peak temperatures and a slower rate of temperature rise. For the 30% GGBS element the temperature model closely matched the in-situ temperature rise for the first 18 hours, but the model over estimated the peak temperature. The curve for the 50% GGBS element closely matched the in-situ temperature rise up until the peak temperature was reached. Thereafter, the differential between the model and the in-situ temperature grew. For the 70% GGBS element the temperature model did not match the recorded in-situ temperatures. It underestimated the temperature rise for a period and then over estimated the temperature rise.

The reliability of the temperature model was investigated further by using it as an input to a maturity method based on the principle of Equivalent Age to establish if its use was valid in predicting in-situ strength. The method was applied for each element cast using the 20^{o}C strength development curves for both the measured and modelled temperatures. The principle of Equivalent Age gives a maturity index in terms of equivalent age. This equivalent age is then applied to the 20^{o}C strength development curve to give an estimate of the in-situ strength. An acceptable estimate of in-situ strength for a decision on striking formwork using the maturity method can only be made when its estimate is greater than or equal to the TMC measured strength and when the TMC measured strength meets the striking criterion. The values determined by the maturity method are presented in Table 3, for both recorded in-situ and modelled temperature inputs to the model.

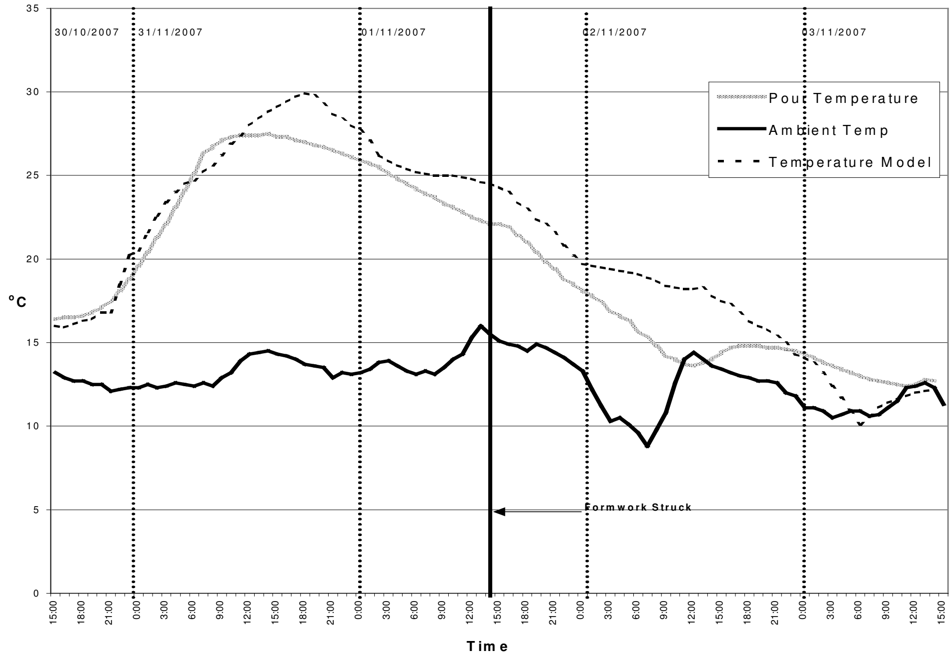

Figure 4 – In-situ, modelled & ambient temperatures, 30% GGBS replacement level

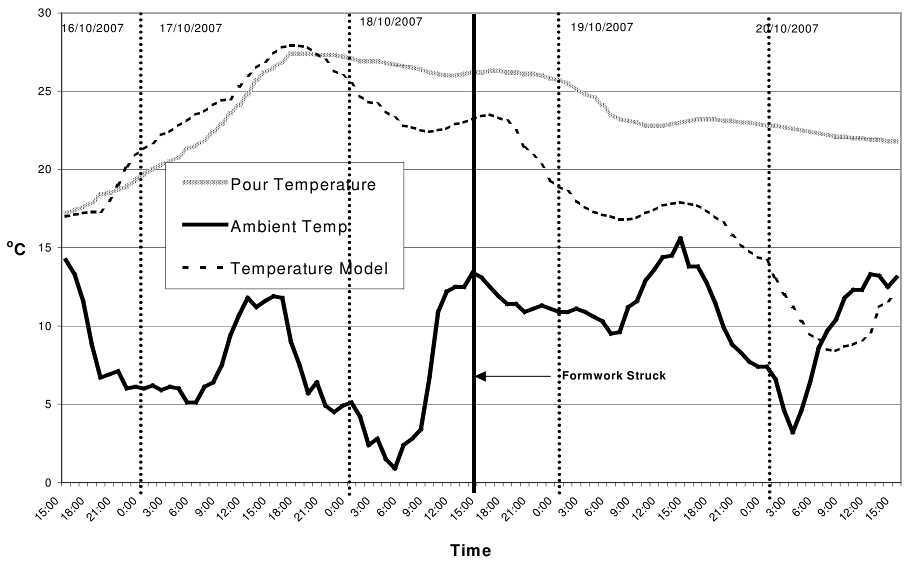

Figure 5 – In-situ, modelled & ambient temperatures, 50% GGBS replacement level

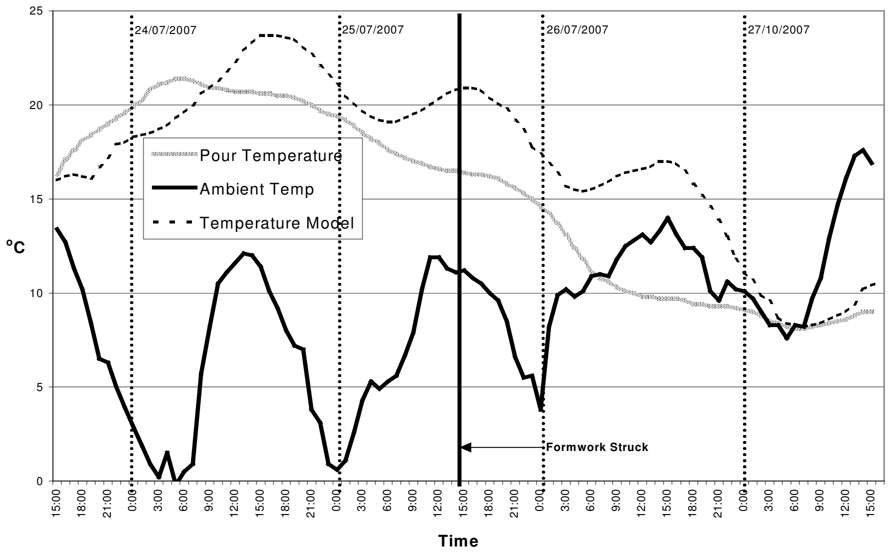

Figure 6 – In-situ, modelled & ambient temperatures, 70% GGBS replacement level

Table 3 – Predicted early age strengths based on the equivalent age maturity model using measured and modelled surface temperatures

Age (days)	**Predicted strength using measured or modelled temperatures (N/mm²)**					
	30% GGBS level		50% GGBS level		70% GGBS level	
	Measured temp.	Modelled temp.	Measured temp.	Modelled temp.	Measured temp.	Modelled temp.
2	18.8	19.6	15.3	14.9	8.6	9.0
3	22.6	24.0	22.5	19.9	14.9	16.1
4	23.8	24.5	28.8	22.9	18.5	18.7

4. Discussion

The context of this study of strength development in CEM II(A-L)/GGBS concretes and the validity of maturity modelling to such concretes was to enable development of a decision-making tool for the striking of formwork. Table 4 indicates which methodology gave a positive or negative response in relation to the measured or estimated strength meeting the requirement of 10 N/mm^2 at two days.

This showed that at two days all the measurement methods gave a '*YES*' decision to strike at a 30% and a 50% GGBS replacement level and a '*NO*' decision to strike at a 70% GGBS replacement level. Based on the experience gained in the experimental work and the decision making yes/no criteria, it was established that it would be possible to develop a flowchart as a decision making tool for striking formwork at early ages that could enhance fast track construction in GGBS concretes. This is reported in a separate paper (Reddy and Richardson, 2008).

Table 4 - Summary of decision outcome using different methodologies for striking formwork at 2 days using a particular CEM II (A-L)/ GGBS concrete mix

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	×	×	×	×	×

5. Conclusions

A study of various assessment methodologies for determining early age in-situ strength of CEM II(A-L) concretes was carried out. The results of the study were used to develop a decision-making tool for determining the striking time for safe and efficient removal of formwork to GGBS concretes at the earliest possible age. This is reported in another paper (Reddy and Richardson, 2008). Various in-situ strength measurement and prediction techniques were investigated for CEM II (A-L)/GGBS concrete elements cast at replacement levels of 30%, 50% and 70% GGBS. The methods included strength testing of standard cured cubes and cubes subjected to temperature matched curing; LOK testing of in-situ specimens; and the application of maturity methods to predict strength, through both measured and modelled temperatures. LOK testing was found to provide valid results for CEM II (A-L)/GGBS concretes at early ages. It was found that the maturity method based on the principle of 'Equivalent Age' could be used to accurately estimate in-situ strengths, but it required verification through an initial test programme. The CIRIA temperature prediction model, for use in a maturity method approach, was shown to be reliable for CEM II (A-L)/GGBS concretes at 30% and 50% GGBS replacement levels, but not for 70% replacement level.

References

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