A Decision Making Tool for the Striking of Formwork to GGBS Concretes

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A project report submitted in partial fulfilment of the requirements for the award of

Diploma In Advanced Concrete Technology

The Institute of Concrete Technology

July 2008
I declare that this entitled “A Decision Making Tool for the Striking of Formwork to GGBS Concretes” is the result of my own work except for cited references. This report has not been submitted for previous accreditation by any other confirming body.

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Name: John Reddy
Date: 30/07/2008
Acknowledgements

I received great support and assistance throughout the course of this study and there are numerous people and parties that deserve my thanks.

My first thanks is to my employer, Ecocem Ireland Ltd., who allowed me the time and funding to undertake this study. Particular thanks to my mentor Peter Seymour for his insight to all matters concrete related, his support and his assistance in editing this report. Thanks also to my MD, Johnny Newell, for his support, encouragement and enthusiasm for my undertaking of this study. A special mention of thanks to my co-worker, Ray Kelly, who assisted in the construction of the formwork on his days off.

To all the staff of Kilsaran Concrete in Clonee a very special thanks. I would have been completely lost without your help. To Nick Davis, Group Technical Manager, for very kindly offering the services and facilities at Clonee for the duration of the work. To Paul O’Hanlon, Area Technical Manager, for assisting with all matters on site in Clonee and to Barry and Gary in the lab for the help with the testing, especially on Saturdays and on Christmas Eve.

A word of thanks to Albert Cole of Hammond Concrete Services in the UK for the hire of the elusive LOK Test apparatus.

Thanks also to Dave Reddy and his associate Al O’Rourke for their help with the concrete pours, cube making and testing.

To Kevin Hyland, Richard Neville and Philip Darcy, thanks for the loan of the tools.

To my tutor, Dr. Mark Richardson of UCD, thank you for your time, interest, encouragement, knowledge and critical review of this study.

Finally, a very special thanks to my father Dave Reddy for the concrete gene he gave me and to the rest of my family and friends for the support and encouragement they continuously offered that was often not acknowledged, but was always appreciated.
Abstract

The early age strength development of concretes made with a blend of GGBS and CEM II (A-L) is different to that of Portland cement only concretes. However, the strength requirements for striking CEM II (A-L)/GGBS concretes are exactly the same as that of Portland cement only concretes. The accuracy of the in-situ strength measurement depends on the method used, and the most accurate method will allow a contractor to obtain the most efficient formwork striking times. To evaluate and compare various in-situ strength measurement techniques, concrete elements were cast at replacement levels of 30%, 50% and 70% GGBS, early age strengths were measured of CEM II (A-L)/GGBS concretes. Standard cured cubes, temperature matched curing, LOK testing and the principle of Equivalent Age maturity method were used to assess the early age strength of the elements cast. Striking criterion was set at 10 N/mm$^2$ to be representative of a suspended slab. The results of the various assessment methodologies were evaluated and compared. The principle of Equivalent Age can be used to accurately estimate in-situ strengths, but needs to be verified by initial test results. The CIRIA temperature prediction model was shown to be reliable for 30% and 50%, but not for 70% GGBS replacement levels. The principle of Equivalent Age and LOK testing can be used for CEM II (A-L)/GGBS concretes at early ages. From a comparison of the various assessment methodologies used in this study, a decision-making flowchart for striking formwork is developed. The decision-making flowchart offers an efficient methodology to make a reliable decision for the prompt removal of formwork to GGBS concretes.
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<th>Description</th>
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<tr>
<td>GGBS</td>
<td>Ground Granulated Blastfurnace Slag.</td>
</tr>
<tr>
<td>CEM I</td>
<td>Formerly OPC or NPC, Portland cement containing 95%-100% clinker by mass.</td>
</tr>
<tr>
<td>CEM II</td>
<td>Portland cement in the strength class 42.5N, containing a cement addition.</td>
</tr>
<tr>
<td>Ca(OH)$_2$</td>
<td>Calcium Hydroxide, hydrated lime.</td>
</tr>
<tr>
<td>C-S-H gel</td>
<td>Calcium silicate hydrates.</td>
</tr>
<tr>
<td>Alite</td>
<td>Tricalcium Silicate, Ca$_3$O.SiO$_4$, C$_3$S.</td>
</tr>
<tr>
<td>PFA</td>
<td>Pulverised Fuel Ash.</td>
</tr>
<tr>
<td>W/C ratio</td>
<td>Free water/cement ratio.</td>
</tr>
<tr>
<td>Pozzalan</td>
<td>Material that exhibits cementitious properties when combined with Ca(OH)$_2$.</td>
</tr>
<tr>
<td>Pozzolanic</td>
<td>Refers to a substance that is a pozzalan.</td>
</tr>
<tr>
<td>TMC</td>
<td>Temperature Matched Curing.</td>
</tr>
<tr>
<td>LOK Test</td>
<td>Non-destructive pullout test.</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>EN</td>
<td>European Norm</td>
</tr>
</tbody>
</table>
List of Equations

**Principle of Equivalent Age**

The principle of Equivalent Age states that a concrete cured for a period $T_1$ at a temperature of $\theta$°C has and Equivalent Age $T_{eq}$ when cured at 20°C. It is given by:

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

Where $\theta$ is the average temperature and $\Delta t$ is the increment in time at $\theta$.

**Simply supported, universally loaded slab equations**

- **Total Load (w) = Dead Load + Imposed Load**

- **Bending Moment (BM) =** $\frac{wl^2}{8}$ kN/m

- **Section Modulus (Z) =** $\frac{bd^2}{6}$ m³

- **Stress =** $\frac{BM}{Z}$ N/mm²
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Chapter One – Background

1.0 Introduction

The early age strength development of GGBS concretes is slightly different to Portland cement only concretes and this can affect site practice, such as varying the minimum time to strike formwork. However, the strength requirements for striking GGBS concretes are no different to Portland cement only concretes. Accurately assessing the early age strength of concrete is a prerequisite to making a decision for striking formwork at optimal timings, especially for GGBS concretes.

This study investigates the early age strength of a limestone cement concrete with various levels of GGBS and presents a decision-making tool for contractors/engineers for the striking of formwork at optimal times for fast track construction using GGBS concretes.

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.

1.1 Criteria for Striking formwork

The decision to remove formwork and allow a structure to support itself is a matter for judgement between the need for speed of construction and for safety during the construction process. The primary criterion for striking formwork is that the concrete has sufficient strength to support its own weight and any construction loads that it
may be subjected to. There are also other factors that need to be considered in setting the criteria for formwork striking and these include:

- Permissible deflection
- Frost damage
- Mechanical damage due to the removal of formwork
- Further mechanical damage due to site operations
- Moisture loss, affecting hydration
- Colour variation
- Finish
- Durability
- Thermal cracking and shock

The minimum striking time is generally calculated by determining the compressive cube strength required to satisfy all the criteria. Best practice is for the cubes to be cured, as near as possible, under the same conditions as the concrete in the element.

The British Standard 8110 (1985) states that formwork supporting cast in-situ concrete in flexure (beams or slabs) may be struck when the strength of the concrete in the element is 10 N/mm$^2$ or twice the stress to which it will be subjected, whichever is the greater. There are no requirements laid out for vertical members (columns or walls) other than to reach the minimum required compressive strength before being exposed to frost and possible damage. Sadgrove (1974) demonstrated through a series of experiments that a compressive strength of 2 N/mm$^2$ before freezing is sufficient to avoid frost damage. The British Standard 8110 gives a more conservative value of 5 N/mm$^2$.

1.2 Strength Development of Concrete

The strength of concrete can be quantified in terms of compressive, tensile and flexural strength. For the purpose of this report strength is to be taken as the compressive strength.
Concrete develops its strength by the hydration of the binder to form a complex series of hydrates. The main products are calcium silicate hydrates (C-S-H gel) and calcium hydroxide (Ca(OH)$_2$). Many factors influence the rate of strength gain of concrete, some of these are:

- Cement Type
- Cement Additions
- Concrete Porosity
- Water/Cement (w/c) Ratio
- Curing
- Temperature
- Section Size
- Insulation

### 1.3 Maturity of Concrete

The strength development of concrete is dependent on the progress of the hydration of the binder. In turn, the rate of hydration is dependent on the reaction temperature. Neville (2002) describes how this leads to the proposition that concrete strength can be expressed as a function of time and temperature - the maturity function.

![Typical Strength-Maturity Relationship](image)

**Figure 1.1** – Maturity Function (From NRMCA)
An example of a maturity function is illustrated in Figure 1.1. It shows strength in relation to an Equivalent Age or a Maturity Index. The maturity index is dependent on the maturity function applied. The relationship between strength and the maturity index must be determined experimentally for the particular concrete being used (Harrison 2003).

Once the maturity index has been established, the maturity method provides a relatively simple approach for estimating in-situ concrete strengths. However, it is limited to the individual test points, and for a large section it may be necessary to take temperature measurements at several points simultaneously to account for variations within the concrete. There are four general steps required to use the maturity method to estimate the in-situ concrete strengths at a point in a concrete element:

- Obtain a strength development curve for a mix at 20°C
- Measure or calculate temperature-time history
- Apply a maturity function using the temperature–time history to determine the maturity index
- Estimate the in-situ strength using the strength development curve and the maturity index

### 1.3.1 Strength Development Curve

The strength development curve a concrete is determined by crushing cubes cured at 20°C at 1, 2, 3, 7 and 28 days.

### 1.3.2 Temperature-time History

The measurement of in-situ temperatures is achieved by placing thermocouples or other temperature sensors into the fresh concrete. The temperatures can be measured manually or by automatic data logging and once the data is collected the temperature-time history can be plotted. Computer generated models also exist that can determine temperature-time history. CIRIA have produced a tool that plots temperature-time history from specific inputs. The temperature-time history is used as an input for a maturity function to determine a maturity index.
1.3.3 Maturity Functions
Numerous maturity functions have been developed to predict the in-situ strength of concrete. Each has their own merits and weaknesses, dependent on a variety of factors such as ambient temperature and binder used. The selection of one function over another is the choice of the user. The reliability of the maturity function should be investigated as to its accuracy in predicting the in-situ strength for given conditions, before it is chosen for use.

1.3.4 Estimating In-situ strength
Once the strength development curve has been plotted and the maturity index has been determined it is possible to estimate the in-situ strength for a particular mix. To do this the strength development curve is expressed in terms of the maturity index at a particular day age. The maturity method when verified by other non-destructive test methods becomes a valuable method in determining appropriate times for stripping of formwork, removal of props or the application of load.

Several maturity devices are commercially available that continuously measure concrete temperature, calculate maturity and display the result of a maturity function digitally. The British Standard 1881 (1986) describes two available types of maturity meters:

A) disposable maturity meters, which are based on a temperature-dependent chemical reaction and are embedded in the concrete surface at the time of casting

B) electrically-operated integrating maturity meters, consisting of a microprocessor coupled to a reusable temperature sensor inserted into a metal tube which is cast into the concrete.

These methods are outside the remit of this report, although further investigation into their use is recommended.
1.4 Binders

1.4.1 Cement
In the past, the most common type of cement available in Ireland has been normal Portland cement (NPC), also known as ordinary Portland cement (OPC) and in recent times as CEM I. This has been widely available in the strength classes of 32.5N and 42.5N. CEM I is now being phased out in Ireland whilst a new class of cement, CEM II is being introduced. CEM I, as a percentage by mass, consists of 95 to 100% clinker. In CEM II, the amount of clinker is reduced and it is replaced with another constituent. This may be limestone fines, flyash or GGBS. The Irish national annex to EN 206 places an upper replacement limit of 50% when using GGBS in combination with CEM II, but it is permitted to use up to 70% GGBS with a CEM I.

1.4.2 GGBS
Ground Granulated Blastfurnace Slag is a by-product of the iron making industry. When the raw materials of iron are melted in a Blastfurnace, the molten slag is lighter in weight than the pig iron and naturally separates from the iron. The molten slag is filtered off and quenched with cold water causing the slag to granulate, forming Granulated Blastfurnace Slag (GBS). Following drying to remove moisture, the GBS is ground to produce GGBS. The chemical composition of GGBS is essentially the same as Portland cement but in slightly different ratios. It contains less lime and more silica.

<table>
<thead>
<tr>
<th>Chemical Constituent</th>
<th>Portland cement</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆O</td>
<td>65%</td>
<td>40%</td>
</tr>
<tr>
<td>SiO₂</td>
<td>20%</td>
<td>35%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>MgO</td>
<td>2%</td>
<td>8%</td>
</tr>
</tbody>
</table>

**Table 1.1 – Chemical Composition of Portland cement and GGBS**

The hydration of GGBS is a latent pozzolanic reaction in that it commences once the Portland cement has hydrated. The cement particles react with water to form calcium hydroxide (Ca(OH)₂), calcium silicate hydrates (C-S-H gel) and at the same time release
heat. This provides the activation energy for the GGBS particles to react with the calcium hydroxide producing C-S-H gel. The hydration of GGBS consumes most of the calcium hydroxide produced during Portland cement hydration and at high GGBS replacement all calcium hydroxide is consumed. The effect of this is that the quality of hardened cementitious matrix is enhanced leading to increased strengths and durability. The implication of the latent reactivity of GGBS is that the amount of heat released from the hydration process is reduced and the timing of heat release is delayed. This is very useful for mass concrete and high strength concrete where the use of GGBS reduces the possibility of thermal cracking in hardened concrete, but it can lead to lower early age strengths at lower temperatures.

1.5 CIRIA Temperature Prediction Model

Harrison (1995) developed a software package, published by CIRIA that models the temperature rise in concrete with given specific inputs. The usefulness of the model is that it can be used in conjunction with maturity functions to predict the in-situ strength of concrete. This means that a desktop exercise can be completed prior to construction that can estimate the in-situ strength. The model takes as inputs:

- Binder Content (CEM I or CEM I and Addition)
- Addition Type and Percentage
- Concrete Density
- Pour Thickness
- Formwork Type
- Formwork Removal time
- Temperature and weather conditions

The model produces temperature rise curves for concretes made with CEM I or CEM I and an addition (GGBS or PFA). The binder used in this study was a combination of CEM II (A-L) and GGBS. The usefulness of the model was investigated using said binder as to how closely it compared to the measured in-situ temperatures, and how this in turn could be used to predict the in-situ strength of concrete.
1.6 Cube Curing Practices

Cubes that are used in determining the striking times of formwork are often ‘cured alongside’ the concrete in the structure. This is normally achieved by placing them close to or on the structure. If this procedure is not used, cubes that are cured at 20°C are used in determining the striking times of concrete. The ‘cured alongside’ and standard cured 20°C cubes do not take into consideration all the factors in the strength gain of concrete, such as section size, insulation and ambient temperature and can give an inaccurate measure of the in-situ strength of concrete. The limitations of ‘cured alongside’ and standard cured 20°C cubes can be overcome with temperature matched curing (TMC).

1.7 Temperature Matched Curing (TMC)

Temperature matched curing operates using a thermocouple placed within a concrete element that is linked to a curing bath via a controller. A schematic of the system can be found in Figure 1.2.

![Figure 1.2 – Temperature Matched Curing](image)
The controller monitors the temperature within the concrete and adjusts the temperature of the curing bath to match that of the concrete. British Standard 1881accurate (1996) requires that at least two cubes be made from the concrete that is placed for each of the required testing day ages. The exposed side of the cube is sealed and the cube is placed in the curing tank. This can be seen in Figure 1.3.

![Cubes wrapped in cling film in the TMC bath](image)

**Figure 1.3** – Cubes wrapped in cling film in the TMC bath

These cubes are then subjected to the same temperature history as the concrete at a selected point in the concrete element. When tested for strength, these cubes give a more accurate estimate of the concrete strength at a selected point in the element at the time of testing than any other method. For use in determining the striking time of formwork the surface of the concrete is critical and the thermocouple should be placed close to the surface in the cover zone.

There are some minor practical disadvantages in the use of TMC. The provision of a TMC bath on site needs uninterrupted power and cabling must be protected on site. Cubes need to be cast on site and transported to a testing laboratory at early ages. However, these disadvantages do not outweigh the benefits of accurately measuring the in-situ strength of concrete.
Temperature matched curing is the most accurate method of measuring the in-situ strength of concrete and determining if the required strength has been reached in a concrete member to strike formwork.

1.8 Purpose of Study

This study measures the early age strength of combinations of CEM II (A-L) and GGBS concretes using a variety of assessment methods. Each assessment method is used to estimate if the criterion for striking formwork of a simply supported slab is met two days after casting.

The accuracy of the assessment methodologies are then evaluated and from this evaluation a decision-making tool for the striking of formwork is presented to assist in the development of site practice allowing for fast track construction with GGBS concrete using primarily a desktop tool.
Chapter Two – Literature Review

2.0 Introduction

This literature review covers the following topics:

- Strength development of GGBS concretes
- Maturity of concrete
- Formwork striking criteria
- Early Age In-situ Strength Assessment Methods

An extensive search to source relevant literature was completed and it was found that very little literature has been published on the subjects considered in this study. Reference material was sourced using the Internet, Dublin Institute of Technology’s library and from friends and colleagues. The sources of web-based material were Science Direct, the UK Concrete Society, the American Concrete Institute and general Internet searches.

2.1 Strength Development of GGBS Concretes

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.

The experiment designed by Clear considered a suite of concrete mixes containing 0%, 50% and 70% GGBS replacement levels and different types of aggregates. Cubes were cast for each mix, cured at 20°C and tested for compressive strength at 1, 2, 3 and 7 days. The purpose of this exercise was to assess when each mix reached the required compressive strengths for striking.
Four of these mixes were cast in 1m$^3$ concrete cubes to simulate a water retaining wall. The other mix was placed in a 250mm bridge deck. All members were cast during the period from October to December. Companion cubes were cast and cured under temperature matched conditions to assess the likely striking times.

For the cubes cured at 20°C it was found that the minimum requirement of 2 N/mm$^2$ for the striking of vertical formwork was met by all the mixes in less than one day. All the mixes also achieved the minimum requirement of 10 N/mm$^2$ the for striking of horizontal formwork by two days.

For the TMC results it was found that Mix 2, containing a binder content of 390kg/m$^3$ and a 70% GGBS replacement level of CEM I, was the slowest to reach the minimum strength requirement of 20 N/mm$^2$ after 72 hours. All mixes reached 2 N/mm$^2$ within one day and reached 10 N/mm$^2$ within two days.

This work, by Clear, illustrated the slower early age strength development of concretes containing high replacement levels of GGBS. It shows how TMC gives a more accurate measure of the early strength of in-situ concrete than cubes cured at 20°C, and that the use of TMC optimises the determination of formwork striking times.

Soutsos et al. (2005) found that the use of supplementary cementitious materials were heavily penalised by standard cube curing regimes.

To demonstrate this an experiment was conducted where a total of six concrete mixes were cured under adiabatic conditions and tested for compressive strength at 1, 2, 3, 5, 7, 14 and 28 days. The target 28-day mean strength for all these was 100 N/mm$^2$. Replacement levels of GGBS were at 20%, 35%, 50% and 70%. The concrete was cast into 100mm cubes. Half were cured at 20°C. The other half were cured in humidity controlled environmental chamber that was set to 90% for a period of five days. These were then transferred to a constant temperature cabinet.

When comparing the strength development of all the concretes cured at both 20°C and adiabatic conditions, it was found that concretes cured under adiabatic
conditions achieved greater strengths than those cured at 20°C. It was shown that early-age strength under adiabatic conditions of GGBS concretes could be as high as 2.5 times of the strength of companion cubes cured at 20°C. The highest strength gain was that of a 70% GGBS replacement level tested at two days. Under adiabatic conditions, which reached a peak temperature of 58°C after 36 hours, the measured cube strength was 78.5 N/mm² compared to 29.8 N/mm² for a cube cured at the standard 20°C. It was also noted that high levels of cement replacement reduced the rate of temperature rise at early ages and had a retarding affect on early age strength development at a constant 20°C.

This work, by Soutsos et al., has shown that the early age strength gain of GGBS concrete is improved under temperatures in excess of 20°C. This indicates the need for TMC to accurately measure in-situ strength of concrete rather than using standard curing at 20°C.

Barnett et al. (2006) declared that the early age strength of mortars containing GGBS was much more sensitive to temperature at higher levels of GGBS replacement, with cooler temperatures having a retarding affect and warmer temperatures increasing the rate of strength gain.

An experiment was conducted in which standard mortars were prepared with replacement levels of 20%, 35%, 50% and 70% GGBS. Three different free water/cement ratios were used at each replacement level to correspond to concretes with 28-day target mean strengths of 40 N/mm², 70 N/mm² and 100 N/mm². The mortars were cast into 50 mm cube moulds and cured at 10°C, 20°C, 30°C, 40°C and 50°C. The 20°C to 50°C specimens were cured in water tanks. The 10°C specimens were wrapped in damp hessian and stored in an incubator. The cubes were tested for compressive strength at a range of six to eight testing ages. The first test age was chosen to correspond to 4 N/mm² with subsequent tests at twice the age of the previous test.
It was found that the early age strength development of mixtures containing GGBS was highly temperature dependent. Under standard 20°C curing conditions, GGBS mortars gained strength slower than Portland cement only mortars. At higher temperatures, strength gain was much more rapid and the improvement in early age strength gain was more significant at higher levels of GGBS replacement. The apparent activation energy was found to be proportional to GGBS replacement levels. The Portland cement only mortar had an apparent activation energy of 34 kJ/mol, whilst for the 70% GGBS mortar the figure was at 60kJ/mol.

This work, completed by Barnett et al., was further evidence for the use of TMC in this study to accurately measure the in-situ strength of concrete.

The work conducted by Barnett et al. (2007) was a continuation of the work completed by Barnett et al. (2006). Here the experimental work was extended to 15 mixes from six mixes. The early age strength of the concrete was found to be as much as 2.5 times of the strength of companion cubes cured at 20°C for levels of GGBS replacement of up to 70%. The purpose of this work was to investigate the early age strength development of concrete containing GGBS to give guidance for its use in fast-track construction.

2.2 Maturity of Concrete

Neville (2002) and Harrison (1995) described the concept and principles of the maturity of concrete. There are numerous maturity functions to predict the in-situ strength of concrete and the selection of one function over another is the choice of the user.

Traditionally maturity functions are expressed in units of centigrade hours (°Ch), but the recent trend has been to express maturity in terms of, “equivalent to X days”. There are many maturity functions available. Soutsos et al (2005) concluded that the Nurse-Saul and Arrhenius functions put forward by Saul (1951) might not be suitable for GGBS concretes as the pozzolanic reaction is more sensitive to temperature than the hydration of cement. The functions put forward by Carino (1991) and Hansen & Pedersen (1997) are based on °Ch and maybe applicable to GGBS concretes.
Weaver and Sadgrove (1971) put forward the principle of Equivalent Age for Portland cements. Harrison (1975) verified the relationship for temperatures in the range 7°C - 27°C and Wimpenny and Ellis (1991) verified the principle of Equivalent Age for a range of combinations of GGBS and Portland cement. Clear (1994) confirmed the principle of Equivalent Age for the replacement of Portland cement with levels of up to 70% GGBS, and Harrison (1995) presented a worked example of the principle Equivalent Age.

Barnett et al. (2007) gave a full review of maturity functions. The functions developed by Chanvillard & D’Aloia and Kjellsen & Detwiler were cited as having the potential to be modified to produce more accurate strength predictions than the functions put forward by Nurse-Saul, Arrhenius, Freiesleben-Hansen-Pedersen and Weaver-Sadgrove.

The literature reviewed has indicated that the principle of Equivalent Age is a reliable maturity function for estimating the in-situ strength of GGBS concretes in combination with CEM I at replacement levels up to 70%. It has not given any indication of the reliability of the function for combinations of GGBS and CEM II’s. As a result, this study investigated the suitability of the principle of Equivalent Age for combinations of GGBS and CEM II (A-L).

### 2.3 Formwork Striking Criteria

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.

BS 8110 (1985) sets out the minimum in-situ strength to be reached before striking concrete members as:

- 5 N/mm² for members in compression to protect against possible frost damage
- 10 N/mm² or twice the stress a member is subjected to for a member in flexure to withstand a load.
Sadgrove (1974) determined that an in-situ strength of 2 N/mm² was sufficient for members in compression to prevent possible frost damage.

Clear (1994) used the requirements determined by Sadgrove for members in compression and the requirements set out by BS 8110 for members in flexure as the minimum in-situ strength requirements for striking formwork in his work.

The requirement set by BS 8110 for members in flexure was used in this study.

### 2.4 Early Age In-situ Strength Assessment Methods

BS 1881 (1996), Clear (1994) and Harrison (1995) described the concept and principles of temperature matched curing (TMC). Harrison also described other methods of non-destructive in-situ strength assessment such as the rebound hammer, maturity methods and the LOK Test.

TMC and the principle of Equivalent Age were used in this study and to accompany these in-situ strength assessment methods the LOK test was also used.

Bungey et al. (1990) provided recommendations for determining the strength of concrete on site at early ages using the LOK test apparatus. This work highlighted the importance of the knowledge of early age strength development of concrete and described the principles of the LOK test and the apparatus, but not its operation.

Bungey et al. carried out LOK tests on a concrete frame building that was being constructed at Cardington in the UK. This was a joint initiative of several British construction associations, research groups and the British government aimed at improving the performance concrete frame structures. One of the purposes of this study was to determine the early age strength of in-situ concrete using the LOK test apparatus and to draw a correlation of these results to the compressive strength of companion cubes. This correlation was also checked against the manufacturer’s recommended correlation between the force measured by the LOK apparatus (kN) and the compressive strength of cubes (N/mm²).
For the LOK tests the combined correlation for all the concretes was found to be very close to the manufacturer’s correlation. The value of the LOK test was clearly demonstrated as a means of verifying that the required strength for striking formwork had been achieved. The LOK test was noted as being carried out quickly and easily without the logistical difficulties in transporting cubes to a testing location and testing them. On this basis, it was used in this study to determine the early age strength of in-situ concrete with regards to whether the minimum strength requirement for formwork striking had been reached.

Petersen (1997) presented twenty years of pullout testing with LOK test and Capo test that was given in terms of 34 major correlations to standard reference tests. The data showed the stability of the correlation not to be affected by the variation in cement type, free water/cement ratio, age, curing conditions, air entrainment, admixtures, fly-ash and shape/type of aggregates up to 40 mm max size. Only the use of lightweight aggregates produced a significantly different correlation. Stable correlations were found to exist of LOK test results and standard cylinder and cube strengths at a 95% confidence limit.

The work presented by Petersen made no mention of the LOK test and GGBS concretes and how GGBS as a replacement may affect the stability of the manufacturer’s correlations. For this reason the LOK test was chosen as another assessment method of the in-situ strength for the concrete cast in this study.

Soutsos et al. (2005) presented a study in which a full-scale, seven-story, reinforced concrete building frame was constructed at the Building Research Establishment’s Cardington Laboratory in the UK. Here the LOK test was used in conjunction with both standard and temperature matched cured cube specimens to assess its practicality and accuracy under site conditions. Strength correlations were determined using linear and power function regression analysis.

### 2.5 Literature Review Conclusion

The literature review has established the originality of this study. No specific testing has been carried out on a comparison of TMC, 20°C cube testing and LOK testing of
in-situ GGBS concrete elements. Some of the literature reviewed used test methods and similar concrete mixes that were used for this study. However, no series of tests reported in the literature matched the combined test methods and concrete mixes investigated in this study.

The literature review highlighted the effects of different levels of GGBS replacement and temperature on the early age strength of concretes. The literature has cited in-situ strength requirements for formwork striking and these were used in this study. The standard 20\(^\circ\)C cured cube has been shown to be a poor representation of early age strength of in-situ concrete and TMC has been cited as the best practice in assessing the early age strength of in-situ concrete. The principle of Equivalent Age and the LOK test have also been recommended as useful assessment methods of in-situ concrete strengths.

The design of the experiment undertaken as part of this study was based on the advice, test results and recommendations of the literature reviewed.
3.0 Overview

The experiment undertaken as part of this study was designed to investigate the early age strength of GGBS concretes to assist in the development of a decision-making process for the striking of formwork. In Ireland, GGBS is typically used at 30%, 50% and 70% replacement levels. When combined with CEM II, the replacement level of GGBS is limited to 50% by the Irish national annex to EN 206. This restricts the use of a 70% GGBS replacement level and forces a 70% GGBS replacement level to be combined with a CEM I.

The experiment was conducted on the site of Kilsaran Concrete, Clonee, Co. Meath. This ensured that the source of concrete and concrete lab where in close proximity, whilst providing a controlled workspace. Three concrete elements (walls) were cast. Each element had the same dimensions, but had different replacement levels of GGBS in the mix. The elements were selected to be 350mm thick to be representative of a typical slab thickness. The dimensions of the walls were 700 mm x 1800 mm x 350 mm to facilitate LOK testing.

3.1 Materials

3.1.1 Designed Mix

The mix used in this project was a designed mix provided by Kilsaran Concrete, which was a typical pumpable mix for structural use in Ireland. 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 replacement of 70% GGBS of CEM II (A-L) was outside the limit set in the Irish national annex to EN 206 and was included for illustrative purposes. The full details of the designed mix can be found in Appendix A.
3.1.2 CEM II (A-L)

The CEM II (A-L) used in this study is in the strength class 42.5N. It has a clinker content, as a percentage by mass, of 80 to 94% and a replacement of limestone fines of 6 to 20%. The European Norm, EN 197-1 lists the limestone fines as having a total organic carbon (TOC) content below 0.50%.

3.2 Methods

3.2.1 CIRIA Temperature Prediction Model

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. An example of the CIRIA Temperature Prediction Model can be found in Figure 3.1. As this study investigated the early strength of GGBS concretes with regards to striking formwork, the surface temperature curve was used for initial estimates. The temperature model indicated temperatures in excess of 20°C, suggesting that higher strengths would be measured using temperature matched cured strength measurement rather than standard cured cubes.

![Figure 3.1 – 0% GGBS Replacement (CEM I only) Temperature Model Curve](image)

Figure 3.1 – 0% GGBS Replacement (CEM I only) Temperature Model Curve
3.2.2 Standard Cube Strengths

A suite of 100 x 100 x 100 mm cubes was cast and was cured at the standard 20°C for each element cast. Cubes were prepared and crushed in accordance with the European Standard 12390-2 & 3. Three cubes were cast for each testing day age. The testing ages of these cubes were 2, 3, 4, 7, 14, 28 and 56 days. A suite of standard cubes can be found in Figure 3.2. The test days of interest for striking a slab are 2, 3, and 4. The test day ages of 7 and 28 are standard test day ages and the test day ages were brought out to 56 days to investigate the late strength development of different GGBS replacement levels. A test day age of 14 days was used to investigate the intermediate strength development between casting and 28 days.

Figure 3.2 – A Suite Standard cubes
3.2.3 In-situ Strength Assessment Methods

A variety of in-situ strength assessment methods were used and assessed during this study. They were, temperature matched curing, the LOK test and the principle of Equivalent Age maturity method.

3.2.3.1 Temperature Matched Curing (TMC)

A suite of companion 100 x 100 x 100 cubes was cast concurrently to the casting of the standard 20°C. Two cubes were cast and tested for each of the same test day ages as the standard 20°C cubes. These cubes were temperature matched cured. Figure 3.3 shows the TMC bath in the concrete lab containing cubes for testing.

![Temperature Matched Curing bath with cubes](image)

**Figure 3.3** – Temperature Matched Curing bath with cubes

3.2.3.2 LOK Test

The literature review has indicated that the LOK test is a robust and reliable non-destructive in-situ test for use in determining the early age in-situ strength of GGBS concretes. Its operation is illustrated in Figure 3.4. The principle behind the method is that the force required to pull out an insert is correlated to the concrete’s compressive strength.
There are two types of LOK inserts: A) the fixed to formwork and B) the floating cup. For this study the fixed to the formwork type is used and is shown in Figure 3.5.

The LOK apparatus is a portable device that can be used quickly and easily without the logistical difficulties associated with making and testing cubes. Carefully planning
is required before casting to position the inserts and site access is required at the time of each test.

The LOK apparatus was not available for hire in Ireland and was sourced from Hammond Concrete in the UK. LOK tests were conducted in parallel to each cube testing day age. One LOK test result is an average of four individual tests from the same region of a section. Seven test day ages were considered for this study, giving a total of 28 LOK tests per element cast. The LOK inserts were positioned in seven rows of two inserts in both faces of the wall, 14 in each face as shown in Figure 3.6, to give a total of 28 LOK tests. The missing insert on the right hand side of the formwork in Figure 3.6 was noted prior to construction.

![Figure 3.6 – LOK inserts fixed to the formwork](image)

3.2.3.3 The Principle of Equivalent Age

The literature review has given the principle of Equivalent Age as the most reliable maturity method when using GGBS concretes. The principle of Equivalent Age states that a concrete cured for a period $T_1$ at a temperature of $\theta^\circ C$ has an Equivalent Age $T_{eq}$ when cured at 20$^\circ$C. It is given by:

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

Where $\theta$ is the average temperature and $\Delta t$ is the increment in time at $\theta$. 
3.2.4 Experiment Schedule

The work was carried out during the winter months. The temperatures in Ireland are relatively low at this time of year, and can have a retarding effect on the early strength development of GGBS concretes. Thus, the results represent a more demanding situation and would be valid for rest of the year when temperatures are higher and the performance of GGBS concretes would be improved. The last test day age was 56 days and the there was a two week lag in casting the elements. This gave a total experiment duration of 70 days. The work commenced on 15\textsuperscript{th} October 2007 and was completed on 24\textsuperscript{th} December 2007. The elements were cast in three consecutive weeks:

- 17/10/2007 – 50% GGBS Element was cast
- 24/10/2007 – 70% GGBS Element was cast
- 01/11/2007 – 30% GGBS Element was cast

A full schedule of the experiment can be found in Appendix C.

To cast the elements concurrently required three TMC baths. Due to the expense and difficulty in sourcing a TMC bath, only one was available for the duration of the work. This meant that the ambient temperature was not the same throughout the work, having an affect on the strength development in each element.

3.2.5 Wall Construction

Construction of the formwork commenced on 13\textsuperscript{th} October 2007. A method statement for the construction of the formwork and the work entailed was provided to Kilsaran Concrete before commencement and can be found in Appendix D.

Figure 3.7 shows how 12 mm starter bars were placed in the ground and two sheets of A393 steel mesh were cut to length, fixed to the rebar and used as reinforcement.
50 mm spacers were fixed to the reinforcement to guarantee a 50 mm cover to the face, which is typical in slabs. The formwork was built around the reinforcement, as shown in Figure 3.8, and braced to add support. Figures 3.9 and 3.10 show the completed formwork in-situ.
Figure 3.9 – Completed formwork

Figure 3.10 – Completed formwork
3.2.6 Casting Process

The concrete was batched in Kilsaran’s mixing plant and delivered by truck to the casting site at the back of their concrete lab. It was delivered straight off the trucks chute in one continuous pour, as illustrated in Figure 3.11.

The concrete was vibrated as it was placed into the formwork. A slump test was carried out at the time of delivery and the companion cubes were cast. 100 mm steel cube moulds were used to cast the cubes for standard curing at 20°C. These totalled 21 cubes, three for each of the seven testing day ages. Plastic 100 mm cube moulds were used for the 14 cubes for TMC, two for each of the seven testing day ages. Plastic cubes were used, as they are more compact than their steel counterparts. Plastic cube moulds make two cubes in each mould, giving a requirement for seven plastic moulds compared to 14 steel cube moulds, which wouldn’t fit in the TMC bath. The experiment site conditions are shown in Figure 3.12.
Figure 3.12 – Slump test, companion cubes and complete wall (background)

The cubes for standard curing were placed in the concrete lab, covered with plastic and left over night. They were stripped the next day and placed in 20°C curing tanks. The TMC cubes were wrapped in cling film, sealed with tape and placed into the TMC bath immediately after casting. These cubes were de-moulded after one day and placed back in the bath. Later on in the experiment when the temperature in the elements had dropped to ambient temperature, ≈ 8°C, the cubes were removed from the TMC bath and stored in water in the concrete lab.

3.2.7 Determining Striking Time

The literature review did not provide a definitive guide with regards to times for striking GGBS concretes. The decision to strike after two days was taken after consulting with contractors who are using GGBS in Ireland. For a section that is represented by the thickness/depth of the wall, it was suggested that two days would be the earliest striking time for a corresponding slab.
3.2.8 Instrumentation

The TMC bath was positioned inside the concrete lab of Kilsaran Concrete, which was adjacent to the casting site. The TMC bath had a digital data logger, Figure 3.13, which recorded the in-situ temperature and acted as the controller to regulate the temperature of the bath and the in-situ temperature. The thermocouple was placed in the cover zone, in the mid section of the element. The TMC bath was run using the temperature at that point in the elements. The thermocouple was fixed to the reinforcement and the cable was run back to the TMC bath. The cable was run so that it was safe from possible interference from movement of people and machinery.

An initial test was conducted to verify the correct operation of the TMC bath and the thermocouple. This was simply pinching the thermocouple to heat the thermocouple up and then releasing it after sometime, allowing it to cool down. This information was downloaded to the data logger and analysed. The test showed the heating up of the thermocouple, the action of the element of the TMC bath being turned on, the cooling of the thermocouple and the action of the element of the TMC bath being turned off. The test was repeated over several cycles successfully, demonstrating that the TMC bath was working correctly.

![Figure 3.13 – Data logger showing thermocouple and TMC bath temperature](image-url)
3.2.9 Testing

The strength measurements used in this experiment were a combination of compressive strength testing of cubes that were temperature matched cured and cured at 20°C, accompanied by an in-situ strength test on the walls, the LOK test.

The LOK apparatus hired had no manual and no literature could be sourced as to the operation of the LOK apparatus. Thus, trial and error, lead to an eventual understanding of the operation of the LOK apparatus.

The test day ages were selected to be at 2, 3, 4, 7, 14, 28 and 56 days and the testing matrix is shown in Table 3.1. The ambient and in-situ temperatures were recorded using the TMC bath’s data logger. The temperature profile was downloaded from the data logger to a laptop for analysis. The same testing regime was applied to each of the three elements cast in this study.

<table>
<thead>
<tr>
<th>Test Day Age</th>
<th>20°C Cube</th>
<th>TMC Cube</th>
<th>LOK Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1 2 3</td>
<td>1 2</td>
<td>1 2 3 4</td>
</tr>
<tr>
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<td>1 2 3</td>
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<td>1 2 3 4</td>
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<td>1 2 3</td>
<td>1 2</td>
<td>1 2 3 4</td>
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<td>1 2</td>
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</tr>
<tr>
<td>56</td>
<td>1 2 3</td>
<td>1 2</td>
<td>1 2 3 4</td>
</tr>
</tbody>
</table>

Table 3.1 - Matrix of test parameters used for each wall cast
Chapter Four – Discussion and Analysis of Results

4.0 Overview

The full results obtained from the experiment completed in this study can be found in Appendix B. This chapter presents an analysis and summary of the obtained results.

4.1 Formwork Striking Criteria

The aim of this study was to develop a decision-making tool for the safe striking of concrete formwork. To achieve this, the criteria required for striking formwork needed to be determined for the elements in question. BS 8110 states that before formwork is struck for elements in flexure, i.e. beams or slabs, the greater of either 10 N/mm² or twice the stress to which an element will be subjected must be reached. Using the criterion for concrete in flexure, twice the stress that a simply supported slab would be subjected to was calculated using the theory set out in Figure 4.1 below.

Figure 4.1 – Simply supported, universally loaded slab
The results of the stress calculations are given in Appendix B and are summarised in Table 4.1. They are based on the following formula:

- **Total Load (w) = Dead Load + Imposed Load**

- **Bending Moment (BM) = \( \frac{wl^2}{8} \) kN/m**

- **Section Modulus (Z) = \( \frac{bd^2}{6} \) m\(^3\)**

- **Stress = \( \frac{BM}{Z} \) N/mm\(^2\)**

<table>
<thead>
<tr>
<th>Slab Thickness</th>
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<th>300mm</th>
<th>350mm</th>
<th>400mm</th>
<th>500mm</th>
<th>600mm</th>
<th>700mm</th>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
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<td>0.9</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
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<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
</tr>
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<td>2.2</td>
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<td>1.0</td>
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</tr>
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<td>3.8</td>
<td>3.1</td>
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<td>9.3</td>
<td>8.0</td>
<td>6.3</td>
<td>5.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

**Table 4.1 – Strength Required (twice actual bending stress) (N/mm\(^2\))**

It can be seen that for most simply supported slabs, except those that are very thin and wide, the value of 10 N/mm\(^2\) is greater than twice the stress that the slab is subjected to.

The concrete element in this study was 350 mm thick and twice the stress to which it would be subjected to, as a slab would be varying from 0.1 to 9.3 N/mm\(^2\) for a span of 1.0 to 9.0m. As the value of 10 N/mm\(^2\) was greater than the highest value of 9.3
N/mm² for a corresponding slab, the minimum requirement for striking the formwork in this study was taken to be 10 N/mm².

**4.2 Cube Results**

Two suites of companion cubes were cast for each element. One suite of cubes was cured at the standard 20°C and one suite was temperature matched cured. Figure 4.2 shows the measured strengths for the cubes that were subjected to a standard curing regime of 20°C. It shows how a high level of GGBS replacement retards the strength development at a constant temperature at early ages. Full cube results can be found in Appendix B. The strength value given for each standard cube is an average of three individual cube results rounded to the nearest 0.5 N/mm².

![Figure 4.2 – Standard Cured at 20°C Cube Results](image-url)
Figure 4.3 shows the measured strengths for the cubes that were temperature matched cured. Here it can be seen that the in-situ strength for the 30% and 50% elements is equal at early ages. The retarding effect of high GGBS replacement levels on early age strength development is again evident. The figure given for each TMC cube is the average of two individual cubes rounded to the nearest 0.5 N/mm².

The cube results at all the replacement levels indicated differences between the TMC data and the 20°C cured data. Where the temperature rose above 20°C for a significant period of time there was an increase in measured strengths in the TMC cubes. This was the case for the 30% GGBS replacement level element for day ages 2 and 3 as illustrated in Figure 4.4.
The effect of elevated in-situ temperatures for the 50% GGBS replacement level can be seen in Figure 4.5 for day ages 2, 3 and 4 with increased measured TMC cube strengths.
The temperatures recorded in the 70% GGBS replacement level element never reached over 20°C for a significant period of time. The cube results of the 70% GGBS replacement element illustrated in Figure 4.6 reflect this and showed how the 20°C cubes can overestimate the in-situ strength of an element with a high level of GGBS replacement. Here a decision could have been made to strike the formwork at two days as 9 N/mm² is almost 10 N/mm², but the in-situ strength measured by temperature matched curing was 8.5 N/mm². These cube results reinforce the conclusion that temperature matched curing is the most accurate measure of in-situ concrete strength at a point in an element.

**Figure 4.5 – 50% GGBS Replacement Level Cube Results**
The higher strength of the 20°C cubes at later testing day ages was due to the curing regime. The standard cubes remained at 20°C for the duration of the experiment, where as the TMC cubes mirrored the temperature of the element, the temperature of which dropped to ambient within a few days. The elements were cast during the winter months when ambient temperatures were low and this has caused the reduction in strength of the TMC cubes compared to the standard cubes at later testing day ages.

The minimum strength requirement for striking formwork has previously been noted as 10 N/mm² and this was the reference strength used in this study. The striking time for the formwork was set at two days. The cube results at two days are presented in Figure 4.7.
Figure 4.7 – Cube results at two days

It can be seen from both the standard and TMC cube results that both the 30% and 50% GGBS replacement elements met this requirement and it was safe to strike the formwork in place after 2 days. The strength of the standard and TMC cubes for both these elements indicated that an earlier striking time than two days was achievable.

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.

The results showed that standard cured cubes could be used to conservatively measure the in-situ strength at two days of GGBS concretes at 30%, 50% and 70% replacement levels. However, the standard cube strengths were not accurate measures
when compared to the TMC results. The accuracy of the 20°C data is compared to the TMC data in Table 4.2 below. The standard cubes were shown in some cases to underestimate the in-situ strength, which could result in longer striking times being set than is required. In other instances the overestimate of the in-situ strength and could lead to premature striking.

<table>
<thead>
<tr>
<th>GGBS Replacement</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Day Age</strong></td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Underestimate</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Overestimate</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4.2 – Standard cured cube estimates compared to TMC cubes

### 4.3 CIRIA Temperature Prediction Model

The temperature model developed by Harrison (1995) and published by CIRIA produces a temperature rise curve based on CEM I or CEM I and an addition type. This temperature model was used to simulate temperature curves for the different GGBS replacement levels of the elements cast to estimate the in-situ strength of concrete.

The binder used in this experiment was a combination of CEM II (A-L) and GGBS. The use of CEM II is not covered by the CIRIA temperature model. However, since CEM II cements in Ireland closely match the performance of CEM I cements, it has been assumed that this model is applicable for the purpose of this study.

The inputs for the temperature model were as follows:

- **Binder content** - 350 kg/m³
- **Addition** - GGBS at 30%; 50%; 70%
- **Element Thickness** - 350 mm
- **Formwork type** - 18 mm plywood
- **Formwork removal** - 48 hours
The results from the temperature model are presented in Figures 4.8, 4.9 and 4.10 and showed both the peak and surface temperature rises. As this study was considering the striking of formwork only the surface temperature curve was considered.

The surface temperature curve produced by the CIRIA temperature model for both the 30% and 50% GGBS replacement levels were above 20°C from a period of 5 hours to the time of striking. The surface temperature curve for the 70% GGBS replacement level also rose above 20°C, but at a later time and for a shorter duration, when compared to the 30% and 50% GGBS replacement level curves. The effect of different levels of GGBS replacement on the temperature rise on concrete can also been seen in the data from the temperature model: higher replacement levels of GGBS result in lower peak temperatures and a slower rate of temperature rise.

![Figure 4.8 - 30% GGBS Replacement Temperature Model Curve](image)

**Figure 4.8 – 30% GGBS Replacement Temperature Model Curve**
4.4 In-situ Recorded Temperatures

The temperature rise and strength development of concrete are dependent on many factors, including ambient temperature. Ideally all three concrete elements in this work should have been cast at the same time so that the only variable in the process was the replacement levels of GGBS. However, as only one TMC bath was available, the three concrete elements were cast in consecutive weeks. The in-situ temperature rise
in each element and ambient temperature was recorded hourly using the TMC bath’s
data logger and are summarised in Table 4.3.

<table>
<thead>
<tr>
<th>Element</th>
<th>Peak Temp</th>
<th>Time to Peak Temp</th>
<th>Time to &lt; 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% GGBS</td>
<td>27.5°C</td>
<td>18 Hours</td>
<td>53 Hours</td>
</tr>
<tr>
<td>50% GGBS</td>
<td>27.4°C</td>
<td>24 Hours</td>
<td>55 Hours</td>
</tr>
<tr>
<td>70% GGBS</td>
<td>21.4°C</td>
<td>14 Hours</td>
<td>30 Hours</td>
</tr>
</tbody>
</table>

Table 4.3 – Summary of Recorded In-situ temperatures

The first element cast contained a 50% GGBS replacement level. Its in-situ
temperature curve along with the measured ambient temperature and modelled
temperature curve is presented in Figure 4.11. It can be seen from the recorded data
that the pours peak temperature of 27.4°C was reached after 24 hours. The in-situ
temperature reached over 20°C after nine hours of casting and remained over 20°C
long after the formwork was stuck. The effect of this can be seen in the TMC cube
results. The ambient temperature dropped close to 0°C during the second night of
casting.
The second element cast contained a 70% GGBS replacement level and its in-situ temperature curve is illustrated in Figure 4.12. The pours peak temperature of 21.4°C was reached after 14 hours. The temperatures reached in this element are much lower than that of the 50% element. The TMC cube results for this element showed how increased levels of GGBS reduced the heat of hydration in concrete and strength at early ages. It was noted that the ambient temperatures during this period were a lot lower than at the time of casting the 50% element. This also had a negative affect on the temperature rise of the concrete. The in-situ temperature reached over 20°C after twelve hours of casting, which was longer than the 50% element and remained over 20°C for a period of less than one day.

**Figure 4.11** – 50% GGBS Replacement Wall: In-situ, Model & Ambient temperatures
The last element cast contained a 30% GGBS replacement level and its temperature curves are shown in Figure 4.13. The pours peak temperature of 27.5°C was the same as the 50% element but was reached after 18 hours. This was six hours ahead of the 50% element and showed the reduction in the development of the heat of hydration with increased levels of GGBS due to its latent reaction. The in-situ temperature reached over 20°C after nine hours of casting, the same as the 50% wall and remained over 20°C until the formwork was stuck. The effect of the temperature rise over 20°C can again be seen in the TMC cube results. The temperature dropped off at a rate quicker than the 50% element after the formwork was struck. The ambient temperature was unusually mild for this time of year and this accelerated drop off of in-situ temperature was not expected. It suggested that a 50% GGBS replacement level generated more overall heat through hydration than a 30% GGBS replacement level in this instance.
4.5 Comparison of In-situ Recorded temperatures and CIRIA Temperature Prediction Model

The accuracy of the temperature model curves compared to the measured in-situ temperature curves varied for each element cast. 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 to a peak temperature of 29.9°C after 27 hours. It dropped back to a similar curve after striking but over estimated by a few degrees throughout.

The temperature model 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, with the temperature model underestimating the in-situ temperature.
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 for the principle of Equivalent Age to establish if its use was valid in predicting in-situ strength.

### 4.6 Maturity Method – Equivalent Age

Various maturity functions have been derived to estimate the in-situ strength of concrete. From the literature review the best maturity function for estimating the in-situ strengths of GGBS concretes is the principle of Equivalent Age put forward by Weaver and Sadgrove. This maturity function was applied in this study.

The temperature-time history in the concrete was plotted using both the CIRIA temperature model and the recorded in-situ temperatures. The strength development curve at the standard curing temperature of 20°C was also plotted for each GGBS replacement level. The principle of Equivalent Age was applied for each element cast using the 20°C strength development curves for both the measured and modelled temperatures.

The principle of Equivalent Age gives a maturity index in terms of “equivalent to X days”. This figure of “X days” is then applied to the 20°C strength development curve to give an estimate of the in-situ strength. A safe estimate of in-situ strength could only be made using the principle of Equivalent Age when its estimate was greater than or equal to the TMC measured strength when the TMC measured strength meets the striking criterion.

The Equivalent Age was calculated for the 30%, 50% and 70% GGBS replacement level concretes at day ages 2, 3 and 4 as these day ages are of most interest for striking formwork on slabs. A comparison was made to the corresponding TMC cube results at the relevant day ages. The calculations of the principle of Equivalent Age and
Equivalent Age strengths are presented in the tables below using both the recorded in-situ and modelled temperatures.

![Table 4.4](image1.png)

*Table 4.4 – Equivalent Age calculation 30% GGBS replacement*

![Table 4.5](image2.png)

*Table 4.5 – Equivalent Age calculation 50% GGBS replacement*

![Table 4.6](image3.png)

*Table 4.6 – Equivalent Age calculation summary 70% GGBS replacement*
4.7 LOK Test

LOK tests were conducted at the same test day ages as the cubes, namely at 2, 3, 4, 7, 14, 28 and 56 days. The impact of the LOK test on the concrete element tested is illustrated in Figure 4.14.

Figure 4.14 – Before and after LOK test

A LOK test results is an average of 4 individual tests on the same region of concrete and the peak tensile force of each individual LOK test is a kN figure. The recorded kN figures were averaged and converted into a N/mm\(^2\) figure using the manufacturers supplied correlation and are presented in Table 4.7. The full LOK test results can be found in Appendix B.

<table>
<thead>
<tr>
<th></th>
<th>30:70 Mix</th>
<th>50:50 Mix</th>
<th>70:30 Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.75 N/mm(^2)</td>
<td>13.8 N/mm(^2)</td>
<td>8.9 N/mm(^2)</td>
</tr>
</tbody>
</table>

Table 4.7 – LOK test results after two days
Using the LOK test data the 30% and 50% GGBS replacement level elements were shown to have reached the requirement of 10 N/mm² after two days and it was safe to strike the formwork. For the 70% GGBS replacement level element the requirement of 10 N/mm² had not been reached and the formwork should have remained in place. The data obtained from the LOK tests have shown it to correlate reasonably well to the TMC cubes at early day ages. The correlation diverges at later day ages.

### 4.8 Discussion

The purpose of this study was to investigate methods to estimate and measure the early age strength of GGBS concretes and to use these methods and data to develop a decision-making tool for the striking of formwork. Table 4.8 indicates which methodology gave a positive or negative response in relation to the measured or estimated strength meeting the requirement of 10 N/mm² at two days.

<table>
<thead>
<tr>
<th>Test Method</th>
<th>20°C Cube</th>
<th>TMC Cube</th>
<th>Equivalent Age Temps</th>
<th>Equivalent Age Model</th>
<th>LOK Test</th>
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<tbody>
<tr>
<td>30% GGBS</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>50% GGBS</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>70% GGBS</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

**Table 4.8 – Safe to strike after 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 a flowchart was designed that could enhance fast track construction in GGBS concretes. This is discussed in Chapter Five.
Chapter Five – Decision-Making Flowchart for the Striking of Formwork

5.0 Introduction

It was confirmed through the experimental work (Chapter Four) that standard cube strengths are not always an accurate representation of in-situ strengths. The decision-making flowchart designed in this chapter is based on the data and experience from the comparison of assessment methods evaluated in this study. The flowchart allows for a systematic assessment and prediction of in-situ strength. This facilitates an efficient, yet safe, decision to be made on the striking of formwork ahead of standard stripping times, if early age strength permits, in GGBS concretes.

The purpose of the flowchart is to develop a relationship between initial testing and the application of a maturity method so that a maturity method can be used to accurately predict the in-situ strength of GGBS concretes for formwork striking.

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 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 run.

The techniques outlined herein are designed to enable a contractor to apply a variety of theory, calculations and testing to make an accurate and safe decision in striking formwork 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 strength assessment throughout a project to a primarily desktop exercise, using established standard cube data. This can therefore speed up construction in a safe and economic manner.

5.1 Decision Making Flowchart

The proposed flowchart is presented in Figure 5.1 with subsections in Figures 5.2, 5.3 and 5.4.

The main steps in the flowchart are:

- Determine suitability of project
- Determination of striking criteria
- Initial Testing
- Verify relationship between maturity estimates and initial test results
- Application of maturity method to subsequent similar concrete elements
Figure 5.1 – Decision-Making Flowchart for the Striking of Formwork

Step 1
Determine suitability of project for the use of decision-making flowchart: The flowchart is to be used where many similar elements are being cast throughout a project, meaning elements of the same type, dimensions and concrete mix. An example is a multi-storey structure where the same slabs are cast as the structure rises. The flowchart could also be applied to other elements such as columns, beams or walls. If the project is not suitable then consider the standard criteria for striking formwork as per specifications.
**Step 2**

Determine the striking criterion, i.e., the minimum strength, for the element in question: This can be found in the relevant standards or may come as an instruction from an engineer.

**Step 3**

Initial testing to determine the measured strength and the Equivalent Age estimated strength. This process requires the steps indicated in Figure 5.2.

![Initial Testing Sub Chart](image)

**Figure 5.2 – Initial Testing Sub Chart**
Steps in the initial testing sub chart (Figure 5.2):

3(a) Conduct temperature matched curing and standard cube testing for the element being considered to obtain a measured strength.

3(b) A non-destructive in-situ strength assessment method, such as the LOK test, may also be used if desired to obtain a measured strength.

3(c) In parallel to the cube testing, record in-situ temperatures and generate a temperature-time curve using the CIRIA temperature model.

3(d) Verify the reliability of the modelled temperature-time curve compared to the in-situ temperature-time curve.

3(e) 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.

3(f) 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.

3(g) Apply 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 the reliability of the model.

3(h) Use the Equivalent Age and the strength development curve at 20°C to give an estimated strength.

Step 4
Verify if the measured strengths obtained from initial testing meet the criterion for striking formwork.

- If yes, strike the formwork and consider the next element.
• If no, continue with initial testing until the criterion has been reached and then strike the formwork.

• The formwork is struck and the next element is considered.

**Step 5**
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.

**Step 6**
If the relationship has been verified, the maturity method illustrated in Figure 5.3 can be used to accurately predict the in-situ strength of subsequent elements of the same type that are cast throughout a project.

![Maturity Method flowchart](image-url)

**Figure 5.3 – Maturity Method flowchart**
**Steps in the maturity method flowchart (Figure 5.3):**

6(a) The temperature-time curve may be generated using the CIRIA model or recorded in-situ temperatures depending on the results obtained during initial testing.

6(b) Use the temperature-time curve to calculate the principal of Equivalent Age to determine the maturity index/equivalent age.

6(c) The strength development curve at 20°C has been determined previously during initial testing and further cube testing is no longer required.

6(d) Use the Equivalent Age and the strength development curve at 20°C to give an estimated strength.

**Step 7**
If the relationship has not been verified, the maturity method will not accurately predict the in-situ strength and further testing, as outlined in Figure 5.4, should be conducted to measure the in-situ strength of subsequent elements of the same type that are cast throughout a project.

![Figure 5.4 – Testing flowchart](image-url)
**Steps in the testing flowchart (Figure 5.4):**

7(a) Obtain a measured strength from results of standard cube testing, test results from TMC or a non-destructive test such as the LOK test.

**Step 8**
Depending on which branch of the flowchart taken, verify if the Equivalent Age estimated strength or the measured strength obtained from testing meet the striking criterion.

- If yes, strike the formwork and consider the next element.

- If no, continue with the maturity method or testing until the criterion has been reached and strike the formwork.

- The formwork is struck and the next element is considered.

**5.2 Flowchart Summary**

This methodology is specific to one concrete mix at one point in one element. Its benefit can be best utilised throughout a project where there are many of the same elements cast. For example, if the relationship between the maturity function and TMC cube strength is established for 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 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.
6.0 Conclusions

6.1 Decision-Making Flowchart

The decision-making flowchart has been designed in this study based on a critical assessment of the methods used to measure and estimate the in-situ strength of concrete. It offers a methodology to make a reliable decision for the removal of formwork. The flowchart can be applied to any concrete mix in any concrete element but it is unique to a selected point within that element and the mix that is used. The selected point is where the thermocouple is placed within an element and it is at that point where temperature-time history is recorded. In this study the thermocouple was placed in the cover zone as the purpose was to determine the early age strength with regards to striking formwork for a suspended slab. The flowchart can reduce the overall testing program of a project, by using the maturity method to reliably predict in-situ strengths of repeated concrete elements. The benefit of using the flowchart determined from test data and experience in this study model is that it can permit a contractor to speed up construction in a safe and economic way.

6.2 Applicability of CIRIA Temperature Prediction Model to CEM II (A-L)/GGBS concretes

The CIRIA temperature model was investigated for combinations of CEM II (A-L) and different levels of GGBS replacement for the elements cast in this study. The results obtained indicate that the temperature model can be used to estimate the early age temperature development of CEM II (A-L) and combinations of 30% & 50% GGBS in concrete. The model was less accurate for 70% replacement levels of GGBS. These results are specific to the elements that were cast and the ambient temperatures that were measured. Further such work should be conducted to verify the usefulness of the
temperature model for combinations of CEM II and different levels of GGBS replacement.

6.3 Applicability of The Principle of Equivalent Age to CEM II (A-L)/GGBS concretes

The principle of Equivalent Age was found to be a valid method of estimating in-situ strengths for concrete that was cast in the 30% and 70% GGBS replacement level elements at two days using both the in-situ recorded temperatures and the temperature model. The principle of Equivalent Age was found to underestimate the in-situ strengths of the 50% GGBS concrete in this study at two days. However, it was found to be a valid method of estimating in-situ strength at three days. At two days, for the 50% GGBS concrete, a sufficient strength was measured using TMC to suggest it was safe to strike. The reliability of the principle of Equivalent Age is mixed but the results suggest that it can be used for combinations of CEM II (A-L) and 30%, 50% and 70% GGBS replacement levels.

6.4 Correlation of LOK Test Results and TMC Cube Results

The LOK test was found to be a reliable test for determining the in-situ strength of concrete cast in this study. It gave the same decision as to strike or not as the results from temperature matched curing at two days. It could therefore be used to safely measure the in-situ strength of concrete and in turn make a decision for striking formwork.

6.5 Recommendations for Further Work

6.5.1 Strength Development of CEM II (A-L)/GGBS concretes

The 70% GGBS replacement level retarded the early strength development to the extent that the striking of formwork would have been delayed by a day for the element considered in this study.

However, after a period of 14 days the in-situ strength of the 70% replacement wall was greater than the 30% replacement wall, this was also the case after 28 days. The
combination of CEM II (A-L) and a 70% GGBS replacement level does not seem to have a diminishing effect on concrete strength other than a slower rate of early age strength gain compared to lesser replacement levels of GGBS.

It produced a lower temperature development curve and a lower peak temperature than the 30% or 50% GGBS replacement level. This is most beneficial for mass concreting where the heat of hydration and thermal cracking is a concern. The constraints set out in the Irish national annex to EN 206 for the use of a combination of CEM II and a 70% replacement level seem overly conservative. Further experiments should be undertaken to confirm this assertion.

Should similar experiments be conducted to this study, there are some considerations that could be given to the experimental process. Cubes could be tested at 1 day and perhaps earlier as this information would more relevant for vertical structures. A CEM II only element could be cast as a control. Finally, all elements should be cast concurrently as they would be subjected to the same ambient conditions and the only variable in the experiment would be the different replacement levels of GGBS.

6.5.2 Maturity Functions

Other maturity functions such as those put forward by Carino & Hanson; Chanvillard & D’Aloia and Kjellsen & Detwiler should be investigated for their use in estimating the in-situ strength of GGBS concretes in combination with different types of CEM II. Commercially available maturity devices also exist and these too should be investigated for their use in estimating the in-situ strength of GGBS concretes. Similar experiments using similar testing methods should be repeated for different sized elements at different binder contents and combinations to verify the usefulness of the decision-making flowchart and to investigate further the reliability of the principle of Equivalent Age for combinations of CEM II and GGBS.
Chapter Seven – References and Bibliography

7.1 References

Barnett et al. (2006) - *Strength development of mortars containing Ground Granulated Blastfurnace Slag: Effect of curing temperature and determination of apparent activation energies*, Cement and Concrete Research 36


Bungey et al. (1990) - *Best Practice guides for in-situ concrete frame buildings - Early age strength assessment of concrete on site*, BRE Report 387


Hansen & Pedersen (1997) - *Maturity computer for controlled curing and hardening of concrete*, Nordisk Betong, V. 1, Pages 19-34


Petersen (1997) - *LOK Test and Capo Test Pullout testing - Twenty years experience*, Non-Destructive Testing in Civil Engineering Conference in Liverpool

Saul (1951) - *Principles underlying the steam curing of concrete at atmospheric pressure*, Magazine of Concrete Research, V.2, No. 6, 1951, Pages 127-140


Soutos et al. (2005), *Fast track Construction with High-Strength Concrete Mixes Containing GGBS*, Seventh International Symposium on the Utilization of High Strength/High Performance Concrete, American Concrete Institute


7.2 Bibliography


2. National Ready Mixed Concrete Association -

3. IS EN 206 – Concrete – Part 1: Specification, Performance, Production and Conformity

4. EN 197 – Part 1: Cement – Composition, specification and conformity criteria for common cements, British Standards Institute 2000

5. EN 12930-2 Testing Hardened Concrete: Making and curing specimens for strength tests

6. EN 12390-3 Testing Hardened Concrete: Compressive strength of test specimens
Appendices

Appendix A – Mix Design

Appendix B – Schedule of Work

Appendix C – Method Statement

Appendix D – Calculations, Results & Graphs

Appendix E – Manufacturers Correlation of LOK Apparatus
Appendix A

Mix Design
## Project Details

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<tbody>
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## Constituent Materials

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<td>Plain</td>
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<td>Kilsaran Concrete</td>
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<td>Plasticiser</td>
<td>Larsen</td>
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## Mix Composition per m³

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<th>MCC</th>
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<th>Aggregate 20mm</th>
<th>Aggregate 10mm</th>
<th>Water litres</th>
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</tr>
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</table>

BL = Blended Mix

We reserve the right to alter the mixes to maintain the characteristics of the concrete in accordance with IS EN 206.

Signed: P. O'Hanlon

Area Technical Manager – Paul O’Hanlon

Date – 20th December 2007

Sheet 1 of 1

Directors: Ed McKenna (Chairman & Chief Executive), T. McCartney, T. McCartney, M.J. Curran, J. Curran.

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