ACTIVATED SLAG FOR PRECAST CONCRETE HOLLOWCORE SLABS: LABORATORY TRIALS AND FIELD INVESTIGATION

Matthew Cruickshank[1], Chaaruchandra Korde[1], Roger P. West[1], John Reddy[2]

1. Trinity College, University of Dublin, Dublin, Ireland
2. Ecocem Ireland Ltd., East Point Development Park, Dublin, Ireland

ABSTRACT. This paper reports on a novel technique for compacting cube specimens for compressive strength testing from low-workability, "dry" concrete, to achieve equivalent density compared to precast prestressed hollow core slabs. It uses this technique to explore the inclusion of ground granulated blast-furnace slag (GGBS) in prestressed concrete in the precast industry, where pre-early age strength is critical for optimizing productivity. Concretes made with 100% CEM I 42.5R in a concrete laboratory and at a precast concrete factory are compared to a 50% GGBS replacement mix. The effects of curing temperature and a new accelerating admixture on the compressive strength of these mixes at two pre-early testing ages are also studied. Here, using the novel compacting technique, the 50% GGBS concrete, cured under three temperature conditions, that is, ambient temperature (approximately 17°C), 20°C, and 35°C, are explored in order to achieve the minimum permissible strength required for stress transfer of the pretensioned cables in the hollow core slabs. With the use of the novel technique, it is now possible in laboratory and site conditions, to demonstrate that the "dry" concrete with 50% GGBS is able to achieve the necessary strength for transfer by 24 hours after casting.

Keywords: GGBS, Curing Temperature, Admixture, Sustainability, Precast Concrete.

Mr. Matthew Cruickshank is a Research Assistant in Trinity College Dublin working on the early activation of GGBS concrete for precast works.

Dr. Chaaruchandra Korde is a Post Doctorate Research Fellow in Trinity College Dublin working on the early activation of GGBS concrete for precast works.

Dr. Roger P. West is an Associate Professor in Trinity College Dublin and is Principal Investigator on the project into early activation of GGBS concrete for precast works..

Mr. John Reddy is the Technical Development Manager of Ecocem Ireland Ltd., Dublin.

INTRODUCTION

Ground granulated blast furnace slag (GGBS) is a by-product of the iron and steel-making industry and over the past two decades has emerged as one of the most commonly used supplementary cementitious materials in the global concrete industry. Despite its utilisation in the industry as a whole, GGBS has failed to establish itself throughout the precast concrete sector. Specifically, GGBS is yet to be used to any great degree in the production of pre-stressed hollow core slabs in Ireland due to the requirement for high pre-early age (24 hours or less) strength at stress transfer and the low early age strength development of slag cements. The value of precast concrete exports from Ireland to the United Kingdom has increased from a very low base in 2006 to €134M in 2017 and thus improvements in sustainability and performance are crucial in order to remain competitive [1]. With GGBS already featuring significantly in the UK ready mixed concrete sector, the same is likely to follow in the precast industry once the technical disadvantage of GGBS (namely, in this context, slow hydration) is overcome.

In addition to its sustainability characteristics, the replacement of Portland cement with GGBS has technical advantages including better solar reflectance, particle packing, low heat of hydration and several aspects of durability [2]. However, due to its latent hydraulic nature, the early age strength development is considerably slower, under standard conditions, than Portland cement. With standard mortars, GGBS replacements of 30, 50, and 70% lead to decreases in pre-early age strength of approximately 50, 70, and 85% respectively compared to 100% CEM I 42.5R mortars [3]. Due to this, the inclusion of GGBS in applications where high early strength is required is much less attractive. Where high early age strength is not a requirement, the inclusion of GGBS is well established - GGBS has been shown to have positive effects on the long term strength of concrete up to a 60% replacement of Portland cement [4].

There are four methods which are typically used to improve the early age strength performance of concretes containing GGBS: accelerating admixtures, finer particle size, increased curing temperature and lower water-cement ratios.

The accelerating admixtures typically used alongside GGBS are chloride-based alkali activators. These admixtures are effective at improving early age strength performance; however their use is usually strongly discouraged in steel reinforced concrete due to the increased risk of corrosion [5]. In this paper, a new chloride-free admixture which has been designed to activate the GGBS in the mix is examined.

In terms of curing temperature, slag cements have been shown to be more sensitive to temperature compared to Portland cement [6]. Also, precast production facilities in temperate climates are often required to heat their products in cold weather conditions to maintain productivity. In Ireland, facilities producing pre-stressed hollow core slabs have heated production beds which increase the temperature of the concrete at early age. In this investigation, a relatively modest pre-early age temperature increase to 35°C is explored.

The concrete used by precast producers in the production of pre-stressed hollow core slabs has a low water-cement ratio and can be described as a zero slump concrete. The reason for this is that the concrete is extruded along a production bed and must maintain its voided shape without formwork. This “dry” concrete can be problematic when casting cube specimens for strength determination because it is difficult to achieve full compaction using standard casting techniques. For this reason, certain precast producers have abandoned the practice of cube casting in favour of monitoring the concrete's maturity [7] [8]. The switch to a maturity measurement has merit but in order to implement it successfully, it is first necessary to cast a large number of specimens which can be accurately tested to measure compressive strength development with time under different curing temperatures. In this paper, the casting method used by a producer is investigated for its suitability for practical use and for research purposes. When it is determined to be unsuitable, a novel weighted vibration-compaction technique is proposed which allows for compressive strength to be more reliably measured with low variability in the precast factory.

METHODOLOGY

In this paper, the work is presented in two parts. The first evaluates the effectiveness of a cube compaction method currently used at a precast concrete factory. Following the evaluation, a second novel method is proposed which resolves the problems identified with the first method.

The second part investigates the impact of 50% GGBS on the same concrete mix and evaluates the ability of a modest temperature increase and a new accelerating admixture to reduce the pre-early age strength deficit caused by the slow early age strength development of GGBS, where early age strength is determined using the novel cube casting technique.

Materials

Concrete for both field investigations and laboratory work was prepared according to the mix design shown in Table 1. The cementitious materials used were cement and GGBS. The cement used was a CEM I 42.5R produced by Irish Cement and the GGBS was produced by Ecocem Ireland. The GGBS has a particle mean size of 11 µm. The two admixtures used were a standard air entraining agent and a new accelerating admixture (Ecocem AcceleR8 Plus). The air entraining agent is used as it enables the concrete to move more easily through the extruder. The mix design has a water-cement ratio of 0.31.

Table 1 Mix Constituents

MATERIALS	MASS (kg/m^3)
20mm Stone	400
10mm Stone	955
Sand	440
Cementitious Materials	360
Water	110
Air Entraining Agent	0.4
Accelerating Admixture (selected mixes)	3.6

Sample Preparation

For each mix, 100 mm cubes were prepared for compressive strength testing. As the concrete has low workability, the samples could not be prepared using standard methods (tamping rod or vibration table). Instead, the cubes were cast using the two methods described presently.

The apparatus used for compaction were a compaction anvil (Figure 1 – A), a lump hammer (Figure 1 – B), a claw hammer (Figure 1 – C) and a vibration table. The compaction anvil plate measured 98mm x 98mm so that it fills the internal plan area of the cube mould.

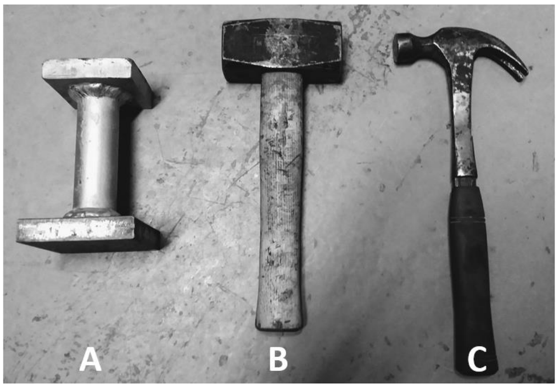

Figure 1 Cube Casting Apparatus – (A) Compaction Anvil, (B) Lump Hammer, (C) Claw Hammer

Method A – Hammer and compaction anvil

Method A is the method used on site at the precast factory. The concrete specimens are compacted in three equal layers. For each layer, fresh concrete is placed inside the cube mould and the compaction anvil is placed on top of the concrete. The concrete is compacted by striking the compaction anvil eight times per layer with the claw hammer. In this investigation, Method A was used as described and subsequently slightly modified by substituting the claw hammer with a lump hammer and by increasing the number of blows per layer.

Method B – Novel weighted vibration compaction

The second method examined in this paper is a novel compaction method which uses a portable weighted vibration compaction technique to cast each specimen. A portable vibrating table vibrates a cube with concrete layers inside and in which a plate of known weight is placed to compact the concrete from above. This method does not involve the use of a hammer and thus is less laborious and also more reproducible because the impact force from a hammer will vary between operators.

On-site Curing

Specimens prepared at the precast factory were cured inside of the fresh hollowcore slabs. The top of the slabs were removed and the moulds were placed inside, sitting on the base of the slab. The top of the slab was covered with a layer of Styrofoam where the concrete was removed to provide insulation. This method was used so that the temperature history, and thus maturity, of the cubes closely mimics that of the slab itself.

Laboratory Curing

Following casting, the cube moulds were wrapped in saturated hessian and a polyethylene sheet to keep the cubes at 100% relative humidity. Cubes cured under ambient conditions were left in the laboratory overnight. Cubes with a defined curing temperature were stored in a temperature and humidity chamber maintained at the desired temperature and 95% relative humidity.

Laboratory Mixing Programme

In the laboratory, five mixes were prepared according to the mix design shown in Table 1. The mixes varied in terms of the amount of GGBS, the curing temperature, and the presence of the accelerating admixture. The conditions for each of the five mixes are given in Table 2.

Table 2 Mixing Programme

MIX ID	CEMENTITIOUS MATERIALS	CURING TEMPERATURE	ACCEL. ADMIX
1	100% Cement	Ambient (~17°C)	No
2	50% Cement, 50% GGBS	Ambient (~17°C)	No
3	50% Cement, 50% GGBS	Ambient (~17°C)	Yes
4	50% Cement, 50% GGBS	20°C	Yes
5	50% Cement, 50% GGBS	35°C	Yes

RESULTS AND DISCUSSION

The results of this experimental and field work are presented in two sections: (i) the need for and the development of a novel casting technique for low-workability concrete and (ii) the impact of a 50% substitution of CEM 1 42.5R with GGBS on the same "dry" concrete and the ability of a modest curing temperature increase and a new chloride-free admixture to counteract the loss in pre-early age strength.

Specimen Casting

Cubes are cast on site using compaction Method A and the results consistently indicate that the concrete strength is sufficient for stress transfer at 24 hours. However, the cubes are not fully compacted (Figure 2) and produce highly variable strength (and density) results which are not representative of the strength of the prestressed concrete slabs actually being produced. From the point of view of the producer, this is not problematic as the casting and testing verifies that the concrete has reached a minimum strength of 25 MPa prior to transfer, despite its inefficiency. However, for research purposes, the accuracy and reproducibility of the results is inadequate.

Figure 2 Cube cast using Method A during field investigation

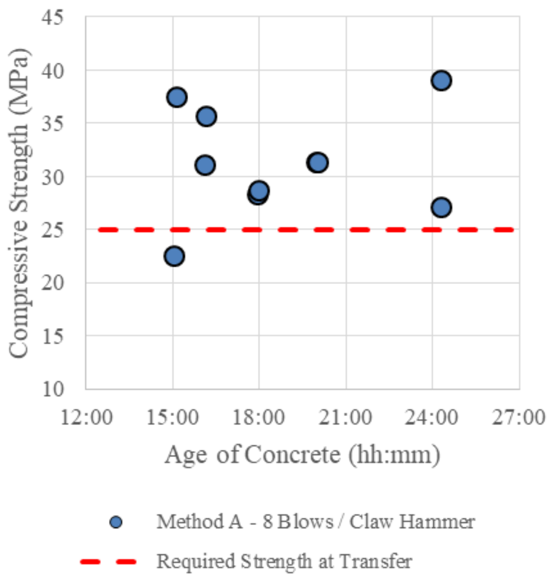

Figure 3 Field investigation of strength development using compaction Method A (8 blows per layer with a claw hammer)

Figure 3 displays the results of a field investigation where the concrete strength was monitored at pre-early age. The cubes were cast using Method A and although all but one very early age cube (15 hours) passed the transfer strength requirement, it is not possible to determine the rate of strength development due to the high variability in the results.

A brief investigation was undertaken to examine whether small procedural changes could eliminate the clear shortcomings of Method A. For example, the claw hammer was replaced by a heavier lump hammer in order to increase the impact force and the number of blows per layer was increased to investigate whether full compaction could be achieved. It was determined that it was possible to achieve compaction much closer to that in the slab manufacture using this revised Method A, however this led to some of the aggregates being crushed and the variability in strength was still high.

The failings of Method A necessitated the development of an alternative compaction technique. Method B was developed by ensuring that full compaction was achieved consistently and independently of the strength and consistency of the operator. Figure 4 displays the cubes made according to Method A (A), an improved Method A (B), and Method B (C). It is clear that the cubes made with Method A do not achieve full compaction whereas the cube made with Method B appears to be much better compacted, if not fully compacted.

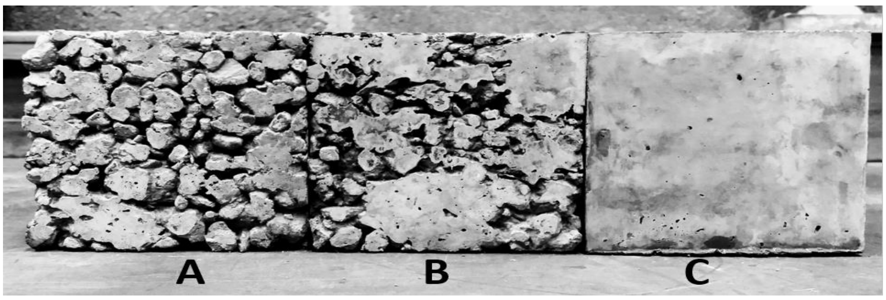

Figure 4 Cubes cast using Method A (A and B) and Method B (C)

Figure 5 presents the results of a second field investigation where Method A and Method B were compared at the factory. During this investigation, cubes made with Method A just achieved the necessary strength only at the 20 hour testing interval, whereas the cubes made with Method B achieved the required strength at all testing ages. In addition to meeting the requirements, the strengths of specimens prepared with Method B had compressive strengths of more than double their Method A counterparts at all testing ages, well exceeding the required strength at 24 hours. This suggests that a modest reduction in cement might be possible, assuming the consistence to deliver compactibility in the hydraulic press is achievable.

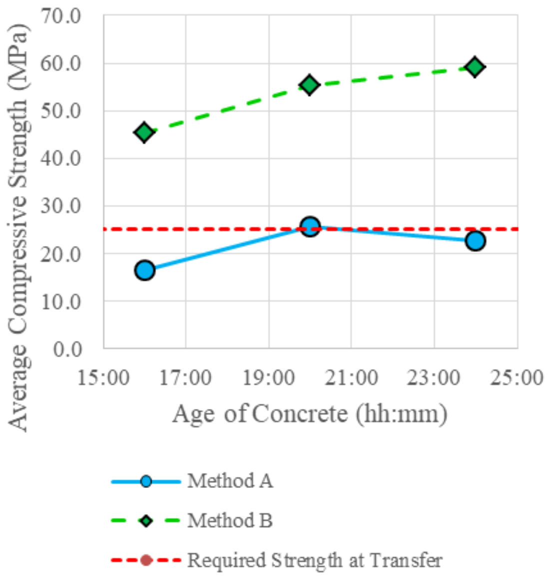

Figure 5 Field investigation of compressive strength for Method A and Method B

GGBS Activation

Figure 6 presents the compressive strength of mixes 1 – 5 (Table 2) tested at two pre-early ages. Mix 1, the control mix cured under ambient temperature, achieved strength of 37 MPa after 20 hours. This strength was much greater than the required strength at transfer of 25 MPa.

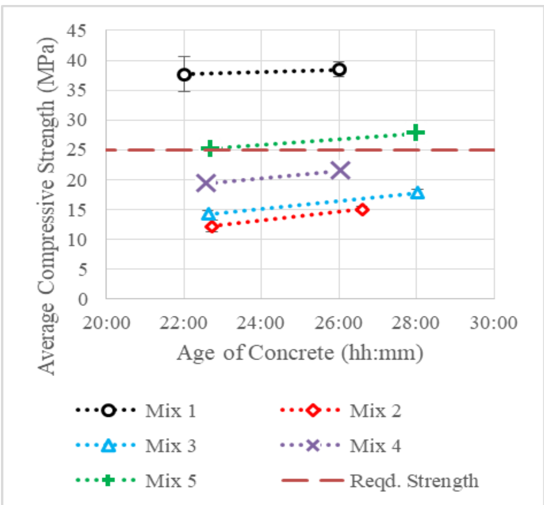

Figure 6 Pre-early age compressive strength of mixes with 50% GGBS under different admixture and curing conditions

A 50% substitution of cement with GGBS (Mix 2) resulted in a decrease in strength of approximately 65%. With identical curing conditions, Mix 2 fell 10 – 13 MPa short of the target strength. Thus the stress transfer in this concrete would have to be delayed significantly until the target strength was shown to exist. This result was not unexpected as the slow early age strength development of GGBS is well established, however it does demonstrate the magnitude of the challenge of including a significant amount of GGBS in prestressed hollow core slabs while maintaining productivity.

The use of the new accelerating admixture (Mix 3) led to a small increased in compressive strength of approximately 2 MPa (to 14MPa) or a 15% improvement relative to Mix 2. This strength improvement was small however the admixture also had a slight water reducing effect which makes the mix move more easily through the production equipment.

Mix 4 was cured in a temperature and humidity chamber maintained at 20°C. This slight increase in curing temperature led to strengths between 19 and 21 MPa at early age. This represents a significant improvement over Mix 3, however the strengths still fell short of the target strength of 25 MPa.

Mix 5 was cured in a temperature and humidity chamber maintained at 35°C. Due to the Irish climate, this is not a temperature that the concrete is likely to reach without heating, even in the summer. However, all precast concrete factories in Ireland have heated production beds and an average temperature of 35°C is well within the limits of their operation. Further, an average temperature of this magnitude is not so high that significant negative consequences for the long term strength of the product are expected [9]. This mix was able to breach the target strength at the first testing age, between 22 and 23 hours. At 28 hours, the average strength was approximately 28 MPa. Thus, with the use of an accelerating admixture and a modest average curing temperature of 35°C, a mix with 50% GGBS is able to meet the pre-early age strength requirements for the production of prestressed hollow core slabs, as demonstrated using the novel cube compaction technique.

CONCLUSIONS

Based on the results of the analysis presented in this paper, the following conclusions can be drawn:

- The concrete used to produce prestressed hollow core slabs in Ireland has a low water-cement ratio, zero slump and can be considered a “dry” concrete. This prevents cube specimen casting using standard methods as the concrete will not compact sufficiently.
- The casting methods used in the factory (Method A) produce results which confirm that the hollow core slabs can be stressed at transfer at 24 hours, however this method shows the system’s inefficiency and is not suitable for research purposes due to incomplete compaction and high variability in specimen strength.
- A novel weighted vibration compaction technique has been developed for casting 100mm cubes and cylinders which achieves full compaction and low variability in compressive strength values.
- A 50% GGBS substitution results in compressive strengths which are approximately 65% lower than 100% CEM I 42.5R at pre-early age under ambient conditions. The introduction of a novel chloride-free admixture increases the strength of the 50% GGBS

mix however the strengths are still 53% - 63% lower than the control strength at pre-early age.

- The use of an accelerating admixture coupled with an increase in curing temperature to 35°C improves the strength of the 50% GGBS to 27 - 34% lower than the control mix at ambient temperature. Although this difference is still significant, using both admixture and increased temperature leads to the 50% GGBS concrete meeting the required strength at transfer of 25 MPa provided the new method is used to compact the cube to demonstrate compliance.

ACKNOWLEDGMENTS

This work is part of the Activated Slag in Precast Concrete Project (ASPC) jointly funded by Enterprise Ireland and Ecocem Ireland. The aims of the ASPC Project are to evaluate the use of GGBS in concrete under chemical and thermal activation in order to enhance the case for the introduction of this more sustainable product type into the precast concrete market. The co-operation of Flood Flooring Ltd, precast manufacturers, for the site work is also gratefully acknowledged.

REFERENCES

1. IRISH CONCRETE FEDERATION. The Industry at a Glance [Online]. Available: http://www.irishconcrete.ie/industry-at-a-glance/. [Accessed 22 April 2018]

2. WEST R P AND KAUR G, G.G.B. Slag graduates – but with what GPA?. International Conference On Advances in Concrete, Structural and Geotechnical Engineering, Pilani, India, 2018

3. KORDE C, CRUICKSHANK M, WEST R P AND REDDY J, Temperature and admixtures effects on the maturity of GGBS mortars for the precast concrete industry. Civil Engineering Research in Ireland, Dublin, Ireland, 2018

4. ONER A AND AKYUZ S, An experimental study on optimum usage of GGBS for the compressive strength of concrete. Cement and Concrete Composites, Vol 29, 2007, pp 505 - 514.

5. ALLAHVERDI A, MALEKI A AND MAHINROOSTA M, Chemical activation of slag-blended cements. Journal of Building Engineering, Vol 18, 2018, pp 76-83.

6. CASTELLANO C, BONAVETTI V, DONZA H AND IRASSAR E, The effect of w/b and temperature on the hydration and strength of blastfurnace slag cements. Construction and Building Materials, Vol 111, 2016, pp 679-688.

7. OLAR A, HEARN N AND WANNAMAKER D, Implementation of the maturity method for zero-slump concrete products. Precast/Prestressed Concrete Institute Journal, Vol 49, No 2, 2004, pp 86-97.

8. LUKE A, KONON W AND PUNURAI S, Maturity Method in Prestressed Concrete Applications. U.S. Department of Transportation, Washington D.C., USA, 2004.

9. YANG K-H, MUN J-S and CHO M-S, Effect of Curing Temperature Histories on the Compressive Strength Development of High-Strength Concrete. Advances in Materials Science and Engineering, Vol 2015, 2015, 12 pp.