Maximising the Potential Use of Ground Granulated Blast-Furnace Slag (GGBS) in Cement: An Irish Investigation

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ABSTRACT: The production of cement is estimated to account for around 8% of carbon dioxide (CO_2) emissions worldwide, and the Irish construction industry yields fifteen million tonnes of CO_2 annually. Measures must be employed to reduce these emissions by incorporating less CO_2 intensive admixtures such as blast-furnace slag, however, the Irish construction industry can often be resistant to change. Therefore, this study aims to investigate the potential implementation of ground granulated blast-furnace slag (GGBS) into the use of cement in Ireland, on the basis of maximisation over optimisation. This research is based on the hypothesis that if GGBS produces drastically less CO_2 than Ordinary Portland Cement (OPC), then maximising its incorporation into cement in Ireland will significantly reduce the Irish construction industry's carbon footprint. Data for the research is accumulated using a mixed-methods approach, combining both quantitative and qualitative techniques. Quantitative analysis considers compressive strength testing of concrete, with various combinations of GGBS and OPC, and qualitative analysis investigates the key barriers to implementation in Ireland, through a series of interviews conducted with five industry professionals. Results indicate that a one-to-one replacement of up to 60% was found to be the maximum substitution proportion of GGBS for OPC, before a drop-off in compressive strength begins to occur. Some of the barriers to its implementation identified that a lack of awareness exists, weather conditions, overarching costs, as well as raising some major safety concerns with its current method of use. Overall, the key contribution of this study reveals the levels and factors at which OPC can be replaced by GGBS in a cement mix, under equal conditions, without a reduction in compressive strength, during cement production in Ireland.

KEYWORDS: Admixture; Concrete; Ground Granulated Blast Furnace Slag (GGBS); Ireland; Ordinary Portland Cement (OPC).

1 INTRODUCTION

In the Irish construction industry, the most commonly used concrete is Ordinary Portland Cement (OPC). However, ground granulated blast-furnace slag (GGBS) is a high-performance alternative to traditional cement which can also minimise the impact on the environment. Molten blast-furnace slag is rapidly soaked with water to GGBS, and the by-product from the manufacture of iron to the production of GGBS has been shown to cause much lower carbon emissions during its production lifecycle [1][2]. To take advantage of this, GGBS can be combined with OPC with a replacement rate of up to 70%, where GGBS is permitted by regulatory standard IS EN 206-1. The higher the mixture percentage, the greater the environmental benefit. When reviewing the literature, previous research fails to acknowledge and highlight the potential advantages of this combination, and most industry reports and surveys appear vague in comparison, particularly within Ireland. Therefore, this study will focus on combining multiple mixtures of OPC with GGBS, from 10% up to 70% GGBS at 10% intervals, and test each mixture to find the most suitable for construction work in Ireland. 70% will be the highest percentage of GGBS used in any mixture to comply with current Irish building regulations.

Concentrating on an important facet of interest, the objective is to find a mixture with the highest percentage of GGBS in the concrete that is found to be satisfactory and fit for purpose in the Irish construction industry. This is achieved by undertaking a sequential mixed method research approach combining both quantitative and qualitative techniques. From a quantitative perspective, concrete tests are undertaken with a variety of cement mix proportions under uniform curing conditions. This is followed by qualitative analysis through a semi-structured interview process, to determine the maximum potential of GGBS and also to discover the limitations that could potentially arise with furthering the utilisation of GGBS in the construction industry in Ireland. Once a suitable mixture with the highest proportion of GGBS is determined, the interviews are conducted with industry professionals who have a range of experience with procuring and manging OPC. The interviews undertaken are used to gauge industry opinion for implementing the mixture in Irish construction projects. Thus, it is anticipated that the results from both the strength tests and interviews will provide the basis for the justification of using GGBS for its environmental benefits in Irish construction.

2 OPC AND GGBS

Estimates suggest that emissions produced from OPC cement may be as much as 8% of global CO_2 emissions [3]. There are four key ways to reduce CO_2 in the cement production process; a change in fuel type to one with a lower carbon content; the addition of a chemical absorption process to gather the CO_2; conversion to a dry manufacturing process using grinding; and adding high volumes of supplementary cementitious materials (SCMs) [4]. One such material is GGBS, which is the supplementary material selected for use in this study. It is argued [5] that using cement blended with SCMs is the most practical and economical method, along with having the most environmental advantages [6]. Research undertaken in South Korea [2] suggest a four phase approach when applying a system boundary for CO_2 reduction; (1) procurement of all constituents in a materials inventory taken from cradle to gate, (2) transportation of the constituents to a ready-mixed concrete plant, (3) in-plant production of the concrete, and (4) transportation of the concrete to a work site to satisfy ISO 14040 criteria. The manufacturing process in this study is conducted under regular temperatures under 15-25 degrees Celsius, which are similar conditions in Ireland, thus perfect for this current research.

Another Korean study [7] uses a statistically produced regression model to calculate CO_2 emission values of different concrete types. However, one of the main limitations of this study is that the proposed regression model is based only on simple linear regression analysis, and while the proposed model showed considerably accurate results in the validation test with regard to certain datasets, its prediction performance is not verified with high-strength concrete like 50 MPa concrete. Nonetheless, these studies confirm that GGBS is much less CO_2 intensive, providing a core basis for this study. From a geographical, environmental and economic perspective, a UK study of the strength development characteristics of concrete containing GGBS [1] provides much of the appropriate baseline for this research. It takes four sample mixes of OPC and GGBS concrete; (70% OPC 30% GGBS), (60% OPC 40% GGBS), (50% OPC 50% GGBS) and a control mix of (100% OPC). This research concludes that after twenty-eight days the compressive strength of the mixes is almost identical as the control mix of 100% OPC, and furthermore, after fifty-six days the compressive strength of all three mixes containing different proportions of GGBS is higher than the 100% OPC mix under regular curing conditions. Moreover, the research delves further into extreme curing conditions, however the limitations of concrete mixes to just 30, 40 and 50% GGBS mixtures fails to highlight enough of the variations desired, such as higher GGBS proportions, thus, OPC content has been clearly shown to be the primary factor for generating CO_2 emissions. Therefore it is crucial to determine the concrete mix with the minimum OPC content and maximum GGBS binder [2].

Results after 36 hours identify all of the mixes except for the 50% OPC 50% GGBS mix, as it satisfied the required compressive strength of 18 to 43 MPa to be utilised in fast track construction. It is determined that per tonne of both OPC and GGBS, 970kg of CO_2 is produced by the production of OPC as opposed to just 55kg in the production of GGB [1]. GGBS mixed concrete is often up to 50% GGBS but can contain up to 70% GGBS [8]. The higher the proportion of GGBS mixed, the higher the durability of the concrete. Conversely, the higher the proportion of GGBS mixed has a negative effect on the early stage strength development of the resultant concrete. For concrete with a high strength requirement at an early age, the GGBS substitution percentage is typically between 20% and 30% to reduce the effect of the slower strength development of the GGBS mixture. For concrete with a high durability requirement or with a strict temperature rise requirement, the GGBS substitution percentage would usually be between 50% and 70% GGBS based [8]. Unlike these studies, this research aims to test a wider variety of mixtures, ranging from 10% GGBS in the mixture, up to 70% GGBS to cater for a large variety of concrete requirements. According to recent studies [9][10], for the first three days of curing, the compressive strength of the GGBS mixes with 40 to 60% GGBS was found to be lower than 100% OPC mixes. However, after the first three days of curing the compressive strength was found to be higher than that of equivalent 100% OPC mixes.

Pulverized fuel ash (PFA) and GGBS have much lower impact regarding CO_2 compared to regular OPC [11]. Whilst PFA incorporated mixes have a water reducing effect which can be used to increase strength by reducing the water content ratio of the mixes, it is unfortunately much less effective as a cementitious material than GGBS. Therefore, it cannot be used in such high quantities and proportions as GGBS regarding the replacement for OPC in concrete mix design. There has been extensive testing on the optimisation of GGBS [12], displaying the potential for cement quality and strength maximisation. Whilst complimenting previous studies focusing on the effects of curing environments on GGBS mixtures [1] and helping to establish an expected pattern to correlate future results, this study also uses a variety of different ratios and water content percentages to help maximise the benefits of GGBS. This new testing will be using a uniform cement mix, replacing only the OPC on a one-to-one replacement with varying proportions of GGBS to create an unbiased comparison of the strength of the concrete produced containing different percentages of GGBS.

Prior research documenting the knowledge base and awareness of industry professionals is scant, particularly within an Irish context. Thus, this is a vital component to incorporating and maximising the use of GGBS in Ireland. Aside from projects with specific requirements to use certain admixtures to a specific percentage, the vast majority of the GGBS used is determined by how much (if any), and suppliers and contractors decide to utilise and without the knowledge of how much GGBS can be used for different tasks and what requirements it can meet. Overall, the lack of past literature and research on the topics of both the compressive strength development of GGBS mixed concrete and the environmental benefits of the utilisation of GGBS over proportions of OPC cement provides a basis for further research. Test mix sample sizes and the economical and geological differences provide grounds for further research regarding the viability and benefits of the use of GGBS admixtures in the Irish construction industry.

3 RESEARCH METHOD

This study is part of a primary investigation which aims to contribute to both industry and academia. On completion of an informative literature review, a sequential mixed method research approach combining both quantitative and qualitative techniques is undertaken. For the quantitative aspect, a broader range of test mixes are used when testing the compressive strength of the concrete cubes, as well as two different curing times of seven days and twenty-eight days. This is to analyse the early age strength of the mixes, assessing its viability of early age construction, as well as the standard curing of twenty-eight days for regular construction concrete. To get the appropriate mix proportions, eight mixes with cubes curing for both seven days and twenty-eight days from each of the eight cement mixes are developed, which will be made up of a 10% GGBS and 90% OPC cement mix and increasing the percentage proportion of GGBS and decreasing the percentage proportion of OPC by 10% up to a maximum of 70% GGBS and 30 % OPC, as well as an eighth control mix of 100% OPC to compare results. Compressive strength tests are conducted by crushing the concrete once the cubes have cured for the allocated time. All of the mixes are composed of the listed proportions of GGBS and OPC, whilst the quantity of stones, sand and water content will remain uniform among all mixes to avoid any unequal results based on extenuating factors such as water retention ability. Figure 1 illustrates the concrete cubes being crushed for compressive strength tests.

Figure 1. Crushing concrete cubes for compressive strength tests

The resultant data is then collected for analysis, and the results will be used to formulate a set of questions for qualitative implementation through the use of an interviewing with five industry professionals including project and site managers working within Irish construction companies. A semi-structured interview format is chosen as this uses an open and closed ended form of questioning, and moreover, questions are asked in no specific order or schedule [13]. This method allows questions to lead from one to another, enabling the interviewee to provide as much information as possible [14]. The aim of the interviews is to focus on the results of the compressive strength test results showing the viability of GGBS mixed with regular OPC, as well as gaining insight to the interviewees levels of knowledge regarding GGBS, its potential benefits and its deficiencies under certain conditions. The results of the interviews are then analysed to determine what, if any, gaps in knowledge regarding the use of GGBS cement among professionals in the Irish construction sector.

From an ethical perspective, the participants are informed of the nature of the research, its purpose and what the resultant data will be used for, prior to commencement of interviews. Also, the identities of those involved remain anonymous and confidential information is not disclosed. All five interviewees are currently based in Ireland working across the Munster region, with a wealth of industry experience in materials procurement in different companies across both Ireland and the UK. Three of the interviewees are site managers, one is a project manager, and one is a quantity surveyor. The interviewees are chosen for their experience and knowledge of the supply chain and are involved with the procurement and acquisition of concrete at different levels of management.

4 RESULTS AND ANALYSIS

Table 1 highlights the compressive strength test results. The percentage of compressive strength lost in the concrete mixes from the addition of the GGBS in place of OPC does not start to occur until the ratio of GGBS is up to 70%. This demonstrates that up 70% GGBS cement will not compromise the concretes strength. The twenty-eight day compressive strength is the highest in the 70% OPC 30% GGBS mixture, representing the optimum mixture ratio of GGBS and OPC under these curing conditions and with the stone, sand and water content ratio as displayed in Figure 2. The drop-off in early age strength occurs at a lower percentage of GGBS as expected, due to ground granulated blast furnace slag naturally curing and developing its compressive strength slower than ordinary Portland cement [9]. However, the drop-off does not occur as drastically as expected, as witnessed in previous studies [1]. There is a clear outlier in the results for the 90% OPC 10% GGBS mixture which has a much lower compressive strength than anticipated. This result may be due to a range of factors such as the curing environment or thermal cracking. Thus, further testing is required to fully understand the cause of the drastic drop-off, which is inconsistent with all other results and previous studies discussed [1][12].

Table 1. Compressive strength test results

OPC / GGBS (%)	Stone (kg)	Sand (kg)	Water Content (ml)	7Day (MPa)	28Day (MPa)	OPC (kg)	GGBS (kg)
100% OPC	2	1.5	655	19.20	25.40	1.170	0.000
90% OPC 10% GGBS	2	1.5	655	14.86	20.89	1.053	0.117
80% OPC 20% GGBS	2	1.5	655	19.02	30.48	0.936	0.234
70% OPC 30% GGBS	2	1.5	655	20.10	33.92	0.819	0.351
60% OPC 40% GGBS	2	1.5	655	19.92	30.29	0.702	0.468
50% OPC 50% GGBS	2	1.5	655	18.80	27.37	0.585	0.585
40% OPC 60% GGBS	2	1.5	655	17.96	26.72	0.468	0.702
30% OPC 70% GGBS	2	1.5	655	16.94	23.30	0.351	0.819

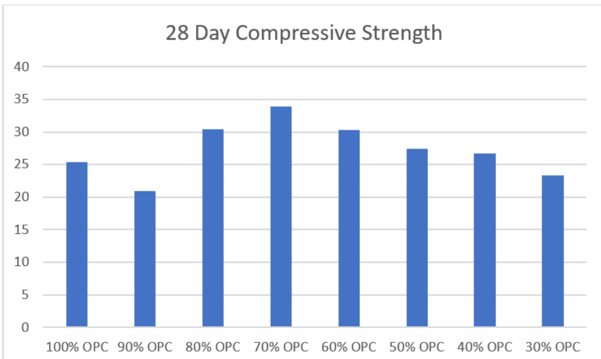

Figure 2. Results after 28 days of curing

Regarding the interviews, when asked if they had ever used GGBS on previous projects, two of the interviewees had used GGBS and three had not. When asked if they were aware that up to 60% of OPC can be replaced by GGBS without a significant decrease in compressive strength, two interviewees were completely unaware that this was possible, whilst the other three had knowledge that it was possible to have a replacement rate of between 30 and 50% percent, and this is occasionally utilised by cement suppliers. However, none were aware that the replacement rate can be as high as 60% percent. All five of the interviewees shared the same view regarding the clients interest in products such as GGBS that can reduce the carbon footprint of their projects. They agreed that clients are showing greater interest in ways to become more environmentally friendly. While three of the interviewees were unsure if cost is currently a barrier to implementation of GGBS, one expressed that it was not a major factor whereas one believed that cost was a major factor. Of the two participants who had used GGBS on previous projects, when probed further about issues experienced using GGBS, both stated that they had experienced issues, as they had been unaware it was used in the cement, and therefore, did not account for the longer curing time. Two of the participants said that a lack of suppliers of GGBS was a major barrier implementation of admixtures, and finally, two participants were unsure and one disagreed that the lack of suppliers was an issue. Figure 3 highlights the compressive test results after seven days of curing, and Figure 4 illustrates the concrete cubes air curing in the laboratory.

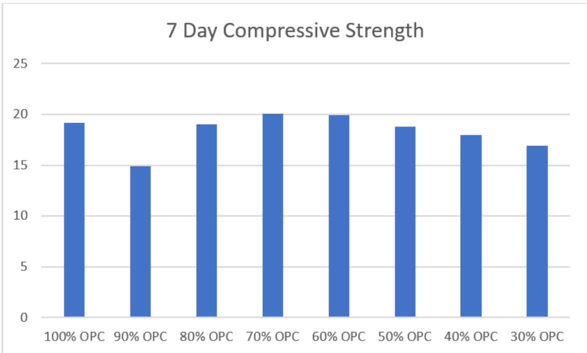

Figure 3. Results after 7 days of curing

Figure 4. Concrete cubes air curing in laboratory

5 DISCUSSION

The test results for the compressive stress of the concrete cubes show that up to 60% of OPC can be replaced by GGBS which is much less CO_2 intensive, and shares a strong correlation with previous studies [1][12]. Also, whilst the results for the early age seven day compressive strengths follow a similar pattern to previous studies [1], there is a very clear disparity in the drop-off in early age strength of GGBS incorporated cubes. The reduction in early age strength is much less than expected in the mixtures containing proportions of GGBS. The reason for this may be due to the curing environment [8] speeding up the expected compressive strength development of the specimens, as different curing environments have been shown to affect the early age strength development in previous testing. To fully understand the effect the curing environment had on the results of the early age strength, the test must be conducted under the same parameters with several more cubes cast for each mix to test each day, as well as a variation of water contents in the mixes to analyse the effect up to seven days to see how the strength developed throughout this early stage [12].

The outlier (90% OPC mixture) is well below the expected result in both the early stage and twenty-eight day results, therefore, thermal cracking may have been the cause of this due to the curing environment and combination for the mixture. However, this is speculative and there may have been a number of factors and thus, due to the unknown it cannot be considered a valid test result [8]. Retesting with the same mixture subjected to a different curing environment is required to investigate if there is a correlation. The reduction involved in the setting and hardening of concrete creates significant heat and can cause large temperature rises, resulting in thermal cracking. Replacing OPC with GGBS reduces the temperature rise and helps to avoid early age thermal cracking. The more GGBS, the smaller the maximum temperature rise which can counter the potential thermal cracking [8]. When conducting the interviews with the five participants, there was notably a wide variety of opinions on the critical barriers to utilising significantly larger proportions of GGBS in the Irish construction environment. Reasons such as cost, awareness and unfavourable weather conditions were all given as decisive factors that could cause contractors to be wary of integrating GGBS, all factors towards a resistance to change. Three of the five interviewees had never used GGBS on their previous projects although one of the interviewees stated that 'various mixes use admixtures to reduce the amount of cement needed in their products'. This is common practice for many cement suppliers and therefore all of the interviewees may have used admixtures such as GGBS on previous projects without being aware.

There are also differences between implementation in the UK where GGBS is typically delivered to the site separately and mixed on site [8], and how it is used in Ireland. This can potentially be a serious health and safety risk, as there are applications where GGBS incorporated concrete is not suitable for. The second interviewee was one of only two that had previously used GGBS on a project and had only been on one project where the client had requirements for a minimum percentage of GGBS. The interviewee also discussed in detail about a previous scenario during the construction of an elevator shaft, where GGBS had been added to the cement mix without their knowledge, 'the next day an excavator clipped the elevator shaft and the whole structure of the lift shaft collapsed, due to the GGBS needing more time to set that the contractor was unaware of'. Two interviewees claimed that they had similar issues with early setting when casting footpaths whilst unaware that the cement they had been supplied contained an unknown proportion of GGBS. This raises concerns with the current method of implementation of GGBS and other admixtures in Ireland, as GGBS under various curing conditions can often have a much slower strength development than standard OPC [1].

6 CONCLUSION AND RECOMMENDATIONS

In essence, this research has highlighted that a replacement rate of up to 60% OPC can be substituted by GGBS with a random mix design, without a reduction in compressive strength. This is due to the outlier of the 90% OPC concrete test cube experiencing a significant and unexpected compressive strength reduction, which did not coincide with previous research. This may have been due to a multitude of factors such as the different mix design or the curing conditions. Further testing will be necessary to identify the root cause of this outlier as it was the only test specimen that fell outside the pattern previously established with past research. The implications of this outlier are that until further testing of more specimens with both the same and a variety of mix designs under multiple curing conditions, all with the 90% OPC 10% GGBS split of cementitious is conducted this result cannot be taken as valid, as the reason for the variation is unknown. Aside from this outlier, the other results all follow the anticipated pattern, displaying that the replacement rate can be replicated with random uniform mix designs. Thus, this identifies that it is possible to achieve these results in multiple scenarios, without having to change the water content ratio to optimise performance. Combining the results from both the tests and interviews, it is identified that there is an interest in procuring more environmentally friendly products and undertaking sustainable practice among industry professionals in Ireland. The research also highlights that incorporating and maximising the percentage of GGBS that they use would not only be environmentally friendly but could also be beneficial when attempting to procure future contracts. Furthermore, the interview process identified some previously unknown and unforeseen issues with the current use of GGBS, such as costs when purchasing in small quantities, cold weather slowing the potential strength development and a lack of awareness on the existence of GGBS. More importantly the research indicates the benefits of using a large percentage of GGBS instead of OPC. If the use of GGBS is to grow in the Irish construction industry, then there must be a framework put into place to raise awareness of its benefits.

If demand for GGBS is significantly increased, then the supply chain will have to be improved to allow for smaller quantity purchases without significantly increasing costs. The interviewees highlighted the issue of unknown quantities of GGBS being used in concrete batches, and acknowledged that currently, there is only one viable supplier of GGBS in Ireland. Thus, this study provides a foundation for further research into the viability of GGBS being incorporated into the Irish concrete supply chain on a larger scale. The issue of weather affecting the early age strength development is undeniably an issue for some areas of construction in Ireland and must also be taken into consideration. This is especially the case if contractors are to begin implementing more mix designs incorporating large levels of GGBS, to avoid issues where early strength development is a high priority. Being unaware of GGBS in cement is an issue, however, an increase in contractors planning, incorporated design mix usage and requesting it from the suppliers could reduce this barrier significantly, with suppliers being less inclined to include GGBS unless specifically requested. These findings confirm that large scale implementation of GGBS can be easily achieved, and the potential benefits can not only be environmentally friendly but also be an important factor when appealing to new potential clients for contracting firms.

However, further research is also be necessary to fully understand why the 90% OPC mix experienced such a large drop in compressive strength. With these results displaying the viability of up to 60% GGBS in mixes, further testing should be conducted on a range of specimens between 60 and 70% GGBS content to find the point at which the drop below the control mix occurs, as well as the testing on the 90% OPC mixtures that must be conducted for validation of results. This could not be conducted in this study due to time constraints. For future testing, it is recommended that each mixture should be made into three testing cubes for each of the curing times. Furthermore, a curing time of twenty-eight days for testing compressive strength is utilised in this research, however, new specifications in the USA suggests comparing strength at a longer period of fifty-six days. Thus, this will require a rethink in current approaches in the industry and provides consideration for further study. Implications for practice are to begin having GGBS requested in a greater quantity of mixes of concrete determined by the procurer, as opposed to the supplier as not only will this reduce the Irish construction industry's contribution of CO_2 emissions, but also will greatly reduce the safety concerns of cement suppliers mixing in GGBS without the user being aware. Nevertheless, the key contribution of this study reveals the levels and factors at which OPC can be replaced by GGBS in a cement mix, under equal conditions, without a reduction in compressive strength, and have major positive implications for cement production in Ireland.

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