



# Strength development characteristics of concrete produced with blended cement using ground granulated blast furnace slag (GGBS) under various curing conditions

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**Abstract.** To reduce the embodied carbon dioxide of structural concrete, Portland cement (PC) in concrete can be partially replaced with ground granulated blast furnace slag (GGBS). In this research effect of partial replacement of cement with GGBS on strength development of concrete and cured under summer and winter curing environments is established. Three levels of cement substitution i.e., 30%, 40% and 50% have been selected. Early-age strength of GGBS concrete is lower than the normal PC concrete which limits its use in the fast-track construction and post-tensioned beams which are subjected to high early loads. The strength gain under winter curing condition was observed as slower. By keeping the water cement ratio low as 0.35, concrete containing GGBS up to 50% can achieve high early-age strength. GGBS concrete gains more strength than the PC concrete after the age of 28 day till 56 day. The mechanical properties of blended concrete for various levels of cement replacement have been observed as higher than control concrete mix having no GGBS.

**Keywords.** Embodied; slag; partial replacement; compressive strength; curing; modulus of elasticity; flexural strength.

## 1. Introduction

“Sustainable development” was defined by Brundtland Commission [1] as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The extensive emission of green house gases (GHG) due to industrialisation and use of fossil fuels in automobiles has led to global warming, climate changes and other environmental degradations, which has further intensified the need for sustainable development [2]. Embodied CO<sub>2</sub> (ECO<sub>2</sub>) is the measure of the amount of CO<sub>2</sub> emissions generated from the energy needed for the raw material extraction, processing, transportation, assembling, installation, disassembly and deconstruction for any system over the duration of a product’s life. The ECO<sub>2</sub> of the construction material is one of the highest, such as for cement it is 913 kg/tonne [3]. There is a general understanding that one tonne of cement production leads to almost one tonne of CO<sub>2</sub> emission. On the other hand, concrete as construction material has been one of the major inputs for socio-economic development of societies. It is the second largest used material after water and it stands at 2 tonnes per capita per year. Hence, the

global production of concrete would continue to increase with time [4].

The supplementary cementitious material (SCM) has been extensively used in the development of high-performance concrete (HPC), which include fly ash, silica fumes, rice husk ashes and ground granulated blast furnace slag (GGBS). Apart from improvement of the properties of concrete in fresh and hardened form, the use of SCM has also reduced the consumption of cement in concrete, thereby reducing the emissions of CO<sub>2</sub> in the atmosphere during manufacturing of cement. The extensive emissions of GHGs such as CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> have led to many environmental issues like global warming, climate change and desertification, etc. There is growing pressure over the construction industry and concrete technologists to reduce the consumption of cement by incorporating SCM and chemical admixtures in concrete. Such kind of concrete are also regarded as “sustainable concrete” [5].

GGBS is a by-product obtained during the manufacture of iron in the blast furnace. It is economically available in large quantities, requiring storage facilities and, therefore, it is suitable for use in ready-mix concrete, in the production of large quantities of site-batched concrete and in precast product manufacturing. Blast furnaces are fed carefully with controlled mixtures of iron ore, coke and limestone at

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a temperature of  $\sim 2000^{\circ}\text{C}$ . The iron ore is reduced to iron and sinks to the bottom of the furnace. The remaining material that floats on top is the slag. The annual production of GGBS in China alone is  $\sim 15$  million tonnes, which is used as raw material in cement production, concrete and pavements [15]. In ref. [6], the authors reported that replacement of cement by slag up to 40% has greater compressive and flexural strength than normal concrete. In ref. [7], the authors studied the behaviour of GGBS-added concrete at elevated temperatures. The cementitious properties of GGBS depends on the chemical composition of the GGBS slag, alkali concentration of the reacting system, glass content of the GGBS, fineness of the GGBS and Portland cement and temperature during the early phases of the hydration process [8].

GGBS has been used as partial replacement to cement in many researches in various forms to develop high-strength and high-performance concrete. Alkali silicate activated slag cement at higher temperatures was also used by studies in refs. [9–12]. In ref. [13], the author worked on the use of pelletised blast furnace slag and its effects on the freeze-and-thaw durability characteristics and reported its good performance in concrete. Although partial replacement of cement by SCM reduced the cement consumption, it entailed some inherent problems associated with their uses. The researchers have developed novel techniques to overcome such shortcomings in the use of SCM [14, 15]. The strength development of concrete having SCM-like slag is relatively slower than normal concrete and usually the optimum compressive strength is achieved at later ages than 28 days and it is recommended to measure the strength of such concrete at 56 days [16]. The use of GGBS has reduced the detrimental effects of silicates in aggregates and the expansion in concrete has been reduced as a result [17]. The Missouri Department of Transportation USA and University of Missouri worked on a joint project on the optimization of cement replacement by slag and identified the range of 40–60% for highest strength development of concrete [18].

The physical properties of GGBS vary significantly from source to source and region to region as there is no standardised manufacturing process. Hence, its effects on the properties of concrete in fresh and hardened form also change significantly. The curing process also affects the properties of concrete made from ordinary or blended cement incorporating GGBS. Water curing was found more effective than heat curing [19, 20]. Slow steam curing of slag-added concrete has gained strength more than water- and air-cured specimen [13].

Concrete made with slag cement has higher long-term compressive and flexure strengths compared to PC concrete and it varies for different curing conditions, mix proportions and age of testing. When PC reacts with water, it forms calcium silicate hydrate (CSH) and calcium hydroxide  $\text{Ca}(\text{OH})_2$ . CSH is a glue that provides strength to the concrete and holds it, while  $\text{Ca}(\text{OH})_2$  is a by-product

and does not contribute to the strength of concrete. When slag is used as part of the cementitious constituent in concrete, it reacts with water and  $\text{Ca}(\text{OH})_2$  to form more CSH gel and increases the strength [21].

Compressive strength of concrete mixtures containing GGBS is increased as the level of GGBS is increased but after an optimum point, which is  $\sim 55\%$  of the total binder content, further addition of GGBS did not improve the compressive strength of concrete. The strength gain is slow in concrete containing GGBS because the pozzolanic reaction is slow and depends on the calcium hydroxide availability [22].

From a structural point of view, GGBS replacement reduces heat of hydration, enhances durability, including higher resistance to sulphate and chloride attack, when compared with normal concrete. On the other hand, it also contributes to environmental protection because it minimises the use of cement during the production of concrete [23]. Form striking time is not increased if the replacement of GGBS in concrete is limited to 50%. [24].

In this research, the effects of the partial replacement of cement with GGBS on the engineering properties of concrete under different curing conditions have been studied. The use of GGBS in concrete tends to slow down the early-age strength, which limits its use in the fast-track construction and post-tensioned concrete which are subjected to high early loads. Early-age strength of concrete containing GGBS can be increased by reducing the water/cement ratio.

## 2. Research significance

The non-uniform physical properties of slag found in various parts of the world and limited research data on the performance of concrete produced with cement having GGBS has been the major motivation for this research. It is expected that the results of the research will add to the existing data on use of blended cement in concrete and its performance under various curing conditions. The early-age strength of blended concrete is relatively less than the normal concrete, which restricts its use in many important projects. Based on various trial mixing, the optimal level of water cement ratio, chemical admixtures and replacement of cement by slag has been established under various curing conditions. This will help in further research in standardising the properties and mixing of the concrete made with blended cements.

## 3. Environmental benefits of GGBS concrete

The environmental profile for the production of 1 tonne of GGBS, compared with typical values of PC, is presented in table 1 by Higgins [25]. For the production of GGBS, the impact for processing the granulated slag to produce GGBS

**Table 1.** Environmental burden for the manufacture of GGBS after [25].

Source	Measured as	Impact	
		Manufacture of 1 tonne of GGBS	Manufacture of 1 tonne of PC
Climate change	CO <sub>2</sub> equivalent	0.05 tonne	0.95 tonne
Energy use	Primary energy	1300 MJ	5000 MJ
Mineral extraction	Weight quarried	0	1.5 tonnes
Waste disposal	Weight to tip	1 tonne saved	0.02 tonnes

**Table 2.** Calculated environmental impacts for 1 tonne of concrete after Higgins [25].

Impact	100% PC	50% GGBS	30% PFA
Greenhouse gas (CO <sub>2</sub> )	142 kg (100%)	85.4 kg (60%)	118 kg (83%)
Primary energy use	1070 MJ (100%)	760 MJ (71%)	925 MJ (86%)
Mineral extraction	1048 kg (100%)	965 kg (92%)	1007 kg (96%)

has been considered and no impact has been taken into account for the production of iron because slag is produced as a by-product in the production of iron, and if not utilised, will go to land fill. The replacement level and the need for extra cementitious content are the important factors in selecting the most sustainable material for concrete production. GGBS is highly cementitious and can usually replace Portland cement by 50% or more.

The environmental impacts benefits of using GGBS and PFA in concrete studied by the UK Concrete Industry Alliance project were tabulated by Higgins [25] and are given in table 2. The environmental impacts are per tonne production of a C30 concrete. As shown in table 2, replacement of 50% Portland cement with GGBS saves 40% CO<sub>2</sub> emissions in concrete. It has a negligible effect on mineral extraction, which is 8%. GGBS and PFA are widely available in the UK and transportation distance between the point of production and the point of use is comparable with those of Portland cement. Higgins [25] concluded that in 2005 the use of GGBS and PFA saved the UK 2.5 million tonnes of carbon dioxide emissions, 2 million megawatt hours of energy, 4 million tonnes of mineral extraction and 2.5 million tonnes of material sent to landfill. The CO<sub>2</sub> emissions are compared in figure 1.

The data published by the Building Material Research Centre of the Aachen University of Technology in Germany using industrial by-products in cement can result in significant savings in energy and reductions in CO<sub>2</sub> emissions. By using 60% blast furnace slag in blended cement, reductions in energy consumption of ~43% and that in CO<sub>2</sub> emissions of ~50% in the production of 1 m<sup>3</sup> of concrete of strength class C25/30 can be achieved (considering the transportation of the aggregate over a distance of 40 km and cement over 80 km) [26].

In Milharbour, London, over 800 m<sup>3</sup> of concrete with 70% GGBS was poured in the raft foundation of Milharbour in London Docklands. Milharbour is Europe's tallest

residential development with over 700 apartments located in two interlinking towers rising up to 50 storeys. The concrete Industry Alliance within a DETR-supported project (1999) calculated the environmental impact of GGBS and found 50% reductions in GHGs for the Milharbour project by using 70% GGBS [27].

In the extension of West Thames College, 35% GGBS was used in the flat slab structure. As PC production is responsible for 6% of the global carbon emissions, its partial replacement with GGBS was environmentally beneficial as less cement was quarried and resulted in less waste product of the steel industry to be land filled. The delivery cost of the blended cement concrete was 2–3% cheaper than the standard concrete mix. Architecturally, the light colour of GGBS concrete provided a nice finish to the fair-faced walls, columns and slabs. Formwork striking times were extended to account for slower strength gain. Vertical forms were delayed from 1 to 2 days and slabs cast in subsequent weeks were delayed to at least 11 days rather than a week for PC concrete. Overall these were acceptable prices to pay for the financial saving and environmental benefit [28].

The Shard is the tallest building in the European Union. It is 310 m high and has 95 floors, including plant floors with 72 habitable floors. The Shard is an unusual mixture of concrete and steel, and has a concrete basement. Here, 75% GGBS was used in the base slab. GGBS was used not only to reduce the propensity for early-age cracking but also to reduce embodied CO<sub>2</sub>. An innovative approach was used on this project to allow construction above and below ground to start simultaneously. High replacement of cement with GGBS has the potential disadvantage of low early-age strength so the concrete was developed such that it could achieve sufficient strength gain to meet initial structural requirements within 14 days, with the full strength being achieved at 56 days. According to the Concrete Centre, the core had already reached 21 storeys high by the time that

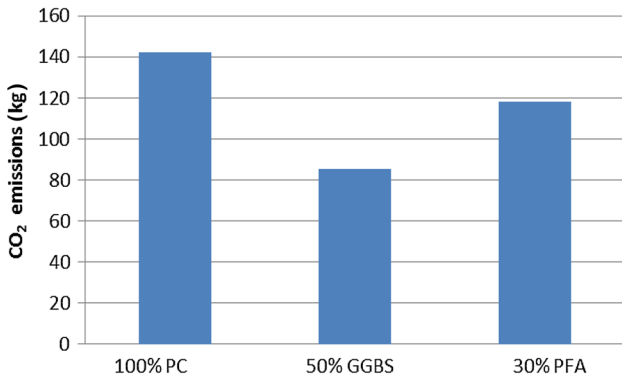


Figure 1. CO<sub>2</sub> emissions after Higgins [25].

700 truckloads of concrete were poured into the basement to form the 3-m-deep raft foundation upon which the tower had to sit [29].

The production of 100 m<sup>3</sup> concrete used 32 tonnes of cement. Replacing 50% cement with GGBS saves 12.96 tonnes of CO<sub>2</sub>. A comparison of the CO<sub>2</sub> emissions of Portland cement and Regen (GGBS) is given in figure 2 [30].

## 4. Experimental program

### 4.1 Material

4.1a *Ground granulated blast furnace slag (GGBS)*: GGBS is a by-product obtained during the manufacture of iron in the blast furnace. GGBS is economically available in large quantities and suitable for production of large quantities of ready-mix concrete at site in precast product manufacturing. The granulated slag is dried and ground to a

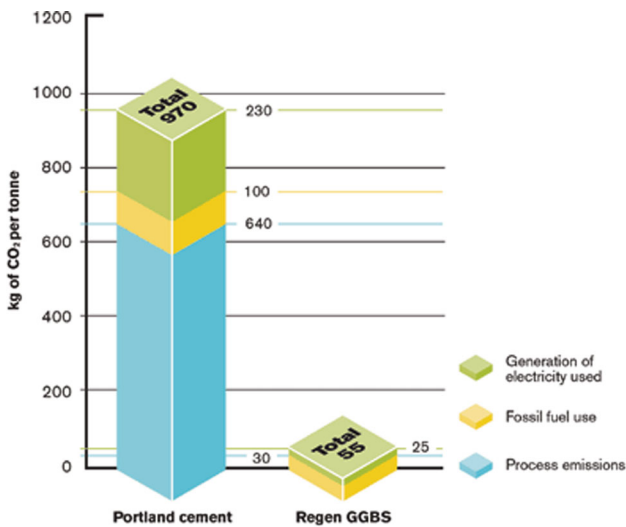


Figure 2. Typical CO<sub>2</sub> emissions for Portland cement and GGBS [30].

Table 3. Typical constituents of GGBS after Hanson (2012).

Constituents	Percentage in GGBS
Calcium oxide (CaO)	40
Silica (SiO <sub>2</sub> )	35
Alumina (Al <sub>2</sub> O <sub>3</sub> )	16
Magnesia (MgO)	6
Other-Fe <sub>2</sub> O <sub>3</sub> , etc.	3

fine powder which is called GGBS. It is off-white in colour and has a bulk density of 1200 kg/m<sup>3</sup>. For a typical GGBS produced in the UK, the chemical constituents are given in table 3.

4.1b *Portland cement*: Ordinary Portland cement (OPC) used conformed to BS EN 197-1 [31] and was classified as CEM-I. The Portland cement was stored in the laboratory to avoid exposure to humidity.

4.1c *Superplasticiser (SP)*: High-performance liquid superplasticizers conforming to BS-EN 934-2 to achieve the required workability was used.

4.1d *Aggregates*: Graded natural sand with a maximum particle size of 5 mm and complying with the requirements of BS EN 12620-1 [32] was used as fine aggregate in the concrete mixes. Thames valley natural aggregates of lime stone were used as coarse aggregate in the concrete mixes. The maximum size of the aggregate used was 20 mm.

### 4.2 Concrete mix proportions

Trial mixes of concrete were redesigned to achieve the 28 days' compressive strength of 60 MPa. In these concrete mixes, the overall maximum water/cement ratio was kept as 0.35. To achieve a practical level of workability and cohesion that was suitable for pumping, concrete was designed for a target slump of 200 mm. A superplasticiser was used to minimise water and cement contents to achieve low free w/c ratio. Mix proportions and details of the mixes are presented in table 4.

### 4.3 Test samples

Two batches of concrete were made for each concrete mix to cast samples. Sixty 100 mm × 100 mm cubes were cast for each mix to measure the compressive strength development according to the British standard test method (BS EN 12390) [33] at the age of 1, 2, 3, 5, 7, 14, 28 and 56 days cured under different curing regimes.

### 4.4 Curing environments

Engineering performance of concrete cured under three different regimes was recorded. The following three



*Strength development characteristics of concrete produced*

**Table 4.** Concrete mix proportions.

Mix	Water (litres)	Binder			Aggregates		w/c	Super plasticiser (ml/100 kg of OPC)	Density (kg/m <sup>3</sup> )
		OPC (kg)	PFA	GGBS (kg)	Coarse (kg)	Fine (kg)			
70PC/30GGBS (30% GGBS)	160	320		137	1285	500	0.35	1200	2400
60PC/40GGBS (40% GGBS)	160	274		183	1285	500	0.35	1200	2400
50PC/50GGBS (50% GGBS)	160	229		228	1285	500	0.35	1200	2400
100PC-Control (No GGBS)	160	457		–	1285	500	0.35	1200	2400

methods were chosen for curing the concrete, which have a close resemblance with the onsite curing environment in the UK.

4.4a *Summer curing environment (C1)*: After casting concrete in the moulds, it was stored for 24 h at a laboratory temperature of  $\sim 20 \pm 2^\circ\text{C}$  and covered with plastic sheets to minimise the loss of moisture. After 24 h, concrete was demoulded and sealed in air-tight plastic bags so that there was no loss of moisture and stored at a laboratory temperature of  $20^\circ\text{C}$ . This curing environment has been titled as C1 and shown in figure 3.

4.4b *Winter curing environment (C2)*: After casting concrete, it was stored for 24 h within the moulds in the environmental chamber controlled at a temperature of  $7^\circ\text{C}$  and 55% relative humidity, which resembles the normal winter temperature in the UK. Moulds were covered with plastic sheets to minimise the loss of moisture. After 24 h, concrete was demoulded and sealed in air-tight plastic bags to avoid any loss of moisture and stored in the environmental chamber controlled at  $7^\circ\text{C}$ .



**Figure 4.** Test cubes under winter curing environment (C2).



**Figure 3.** Test cubes under summer curing environment (C1).



**Figure 5.** Concrete cubes under water curing environment (C3).



Figure 6. Compressive strength test using Avery Denison 2500 kN machines.

Table 5. Compressive strength development of various concrete mixes for summer environment C1 and winter environment C2, expressed as % of 56 days' strength.

Age (days)/compressive strength (MPa)									
Curing	1 D	38 h	2 D	3 D	5 D	7 D	28 D	56 D	Difference (MPa/%)
<i>70PC/30GGBS</i>									
C1	24.5	32.0	37.0	49.5	–	56.5	68.5	74.0	5 (6%)
	33%	43%	50%	67%		(76%)	(93%)	(100%)	
C2	9	17	22.5	31	–	46	57	69	
	13%	25%	33%	45%		67%	83%	100%	
<i>60PC/40GGBS</i>									
C1	18.5	30.0	38.5	45.5	–	58.5	71.5	81.5	13.5 (16%)
	(23%)	(37%)	(47%)	(56%)	–	(72%)	–	(100%)	
C2	3.5	12	18	24.5	–	58.6	62	68	
	5%	18%	27%	36%	–	86%	91%	100%	
<i>50PC/50GGBS</i>									
C1	9.0	20.5	28.5	–	46.0	53.5	68.0	73.0	10.5 (15%)
	(12%)	(28%)	(39%)		(63%)	(73%)	(93%)	(100%)	
C2	1.5	6	9.5	–	23.5	28.5	55	62.5	
	2%	10%	15%		38%	46%	88%	100%	
<i>100PC-Control</i>									
C1	43.5 (62%)	49.5	54.0	58.0	–	67.0	69.0	70.5	0.5 (<1%)
		(70%)	(77%)	(82%)		(95%)	(97%)	(100%)	
C2	13	23	30	38	46	56.5	64.5	70	
	19%	33%	43%	55%	66%	81%	92%	100%	

Concrete cubes cured under the C2 curing environment as shown in figure 4.

4.4c Water curing environment (C3): After casting concrete in the moulds, it was stored at laboratory temperature of 20°C and was covered with plastic sheets. After 24 h, the concrete was demoulded and immersed in a water chamber controlled at a temperature of 20 ± 2°C. Concrete stored under curing environment C3 is shown in figure 5.

## 5. Observations and analysis

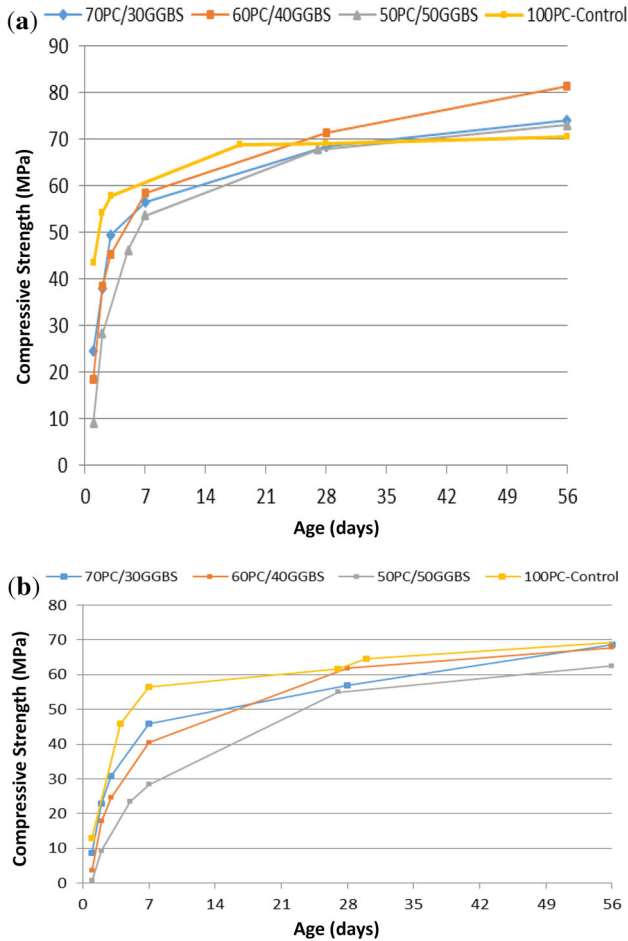
### 5.1 Compressive strength development of GGBS concrete

Two cube specimens from each mix and curing regime were tested for compressive strength using an Avery Denison 2500 kN machine as shown in figure 6. In the case of >10% difference in two results, a third specimen was also tested. The concrete samples cured under regime C3

## Strength development characteristics of concrete produced

**Table 6.** Compressive strength at the age of 28 and 56 days cured at C3.

Concrete mix	Test age days/comp strength (MPa)	
	28 days	56 days
70PC/30GGBS	72.0	75.0
60PC/40GGBS	72.0	82.0
50PC/50GGBS	68.0	74.5
100PC-Control	77.0	79.0



**Figure 7.** Compressive strength development of GGBS concrete under different curing conditions. (a) Under curing condition C1, (b) Under curing condition C2.

were dried at room temperature for 3 h before testing. The specimens were loaded at a rate of 0.4 N/s until failure, following the method described in EN 12390-3 (2009).

## 6. Results and discussion

The strength for various mixes of concrete under two curing conditions C1 and C2 are shown in table 5. The compressive strengths of GGBS concrete under water curing C3 are

given in table 6. The strength development of blended concrete under C1 and C2 conditions is compared with PC for different mixes in figure 7.

### 6.1 Strength development of blended concrete with GGBS

The strength development in blended concrete at the early ages decreases with the increase of GGBS content as compared to PC. There is a marked difference in strength gain between the 3 and 7 days' compressive strength; however, this difference is negligible at 28 days. This shows that initially the strength gain of GGBS concrete is slow but it enhances rapidly between 7 and 14 days. The specified strength of GGBS concrete at 28 days is more than PC, which supports its use for structural concrete and other major works. The 56 days' compressive strength is highest for 60PC/40GGBS combination under summer environment, which represents the optimum level of cement replaced by GGBS for the particular batch of GGBS used in this research.

Maximum cement saving has been achieved for mix 50PC/50GGBS, which has reduced the cement consumption by 50%, that is, 229 kg/m<sup>3</sup>. The 28 days' compressive strength under summer condition of curing for 50PC/50GGBS is almost the same as 100PC with no GGBS. This enables greater opportunity for saving cement and thereby reducing the emission of GHG. The average 56 days' strength of GGBS concrete under summer environment of curing is more than PC for all mixes.

It can be seen that all the concrete mixes cured under regime C1, except 50PC/50GGBS, have satisfied the requirement of 25 MPa, compressive strength after 38 h. Except 50PC/50GGBS, all of the other concrete mixes cured in the C1 environment had strengths in the range of 18–43 MPa at the age of 1 day, which is sufficient to be used in fast-track construction. It can be seen from figure 7 that all of the concrete mixes have nearly the same 28-day strength, but there is a greater increase in the compressive strength of 60PC/40GGBS than the other mixes at 56 days.

It is concluded that the concrete containing 30%, 40% and 50% GGBS gains more strength than the PC concrete after the age of 28 days, which is according to the earlier research [34].

At 56 days, the strengths of 70PC/30GGBS, 60PC/40GGBS and 50PC/50GGBS are 5%, 15.5% and 3.5% higher than the 100PC-control concrete mix, respectively, under C1 curing environment.

### 6.2 Strength development of concrete under various curing conditions

The strength development of GGBS-blended concrete under two extreme conditions are shown in table 5 and

figure 8. At lower replacement value of cement by GGBS (70PC/30GGBS), the strength development under winter C2 is slower than summer condition C1. Under summer condition C1, GGBS-blended concrete gains almost half of its 56 days' strength at the age of 2 days, where, under C2, the level is achieved at approximately 4 days. The strength gain after 7 days is, however, at the same pace, and at 56 days, there is no much difference in the compressive strength under the two curing conditions. This difference (i.e., 69 and 74 MPa, ~6%). This difference increases to ~15% for the other two cases of blended concrete. The difference for PC only is negligible.

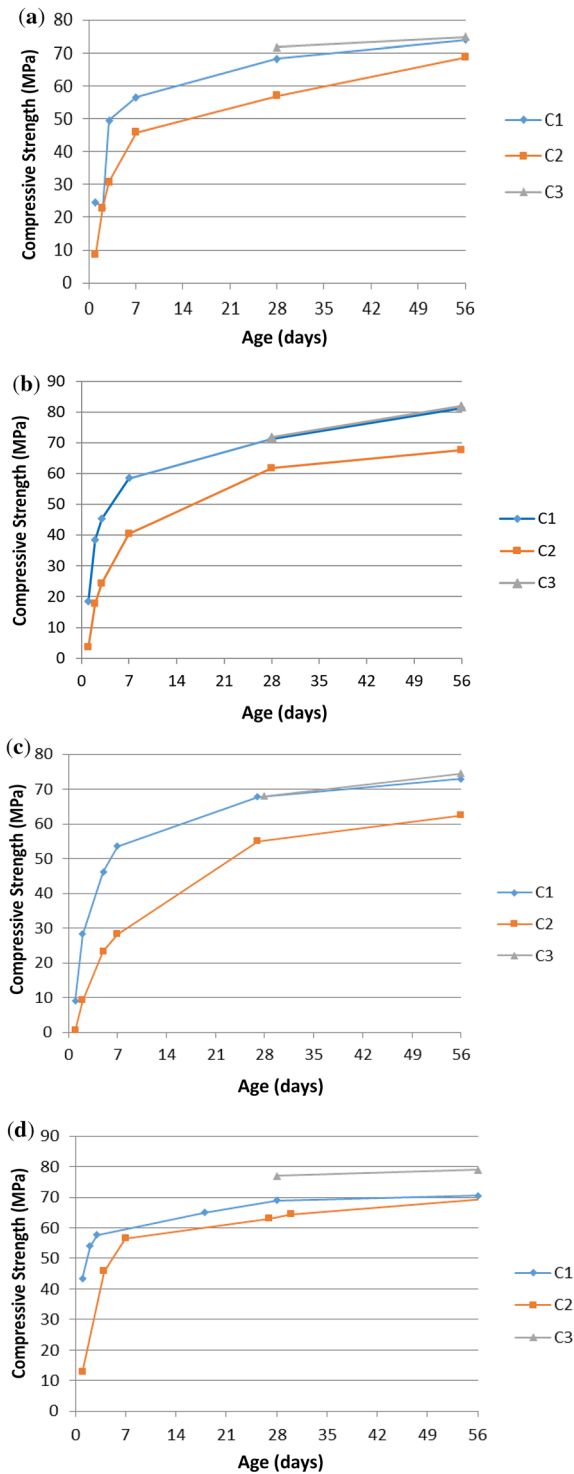
The strength gain under winter conditions at the early ages before 3 days is <20 MPa for 60/40 and 50/50 mix. It is concluded that in winter for GGBS concrete up to 50% special care should be taken regarding the temperature of the curing environment at early ages.

The strength development for 70PC/30GGBS, 60PC/40GGBS, 50PC/50GGBS and 100PC-Control concrete mixes under different curing regimes are compared in figure 7. In all concrete mixes, the strength development under curing regime C2 is lower than the strength development under curing regimes C1 and C3.

As in curing regime C1, concrete was cured in sealed plastic bags to minimise the loss of moisture, all the concrete mixes have nearly the same 28-day strength as that of the concrete mixes cured under regime C3, except the 100PC-Control concrete mix which has gained more strength at the age of 28 and 56 days under regime C3 than the other curing regimes. From these results, it can be concluded that at the curing temperature of 20°C for GGBS concrete mixes there is not much difference in the ultimate strength if it is cured in sealed bags to minimise the loss of moisture or cured under water. For PC concrete mixes, the ultimate strength is higher if it is cured under water than the other curing regimes.

### 6.3 Comparison of flexural strength and modulus of elasticity of GGBS-blended concrete under various curing conditions

For each concrete mix, flexural test was performed after curing in three curing regimes for 28 days. Flexural test results for the different concrete mixes cured under different regimes are given in table 7. The flexural strength of GGBS concrete and PC concrete cured under the different regimes are compared in figure 9. Concrete cured under C2 (7°C) curing regimes have slightly lower flexural strength than the other regimes considered. Concretes cured under the C3 (curing at 20°C under water) regime have higher flexural strength for GGBS and 100PC-Control concrete mixes than those cured under the C1 (20°C) environment.



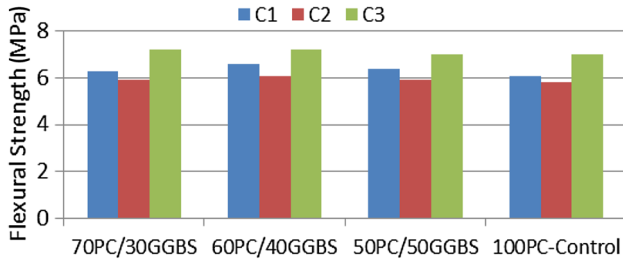
**Figure 8.** Comparison of strength development for various mixes under different curing conditions. (a) 70PC/30GGBS, (b) 60PC/40GGBS, (c) 50PC/50GGBS, and (d) 100 PC control mix.

The 60PC/40GGBS concrete mix gained slightly more flexural strength than the other concrete mixes cured under different curing regimes. The 70PC/30GGBS and 50PC/

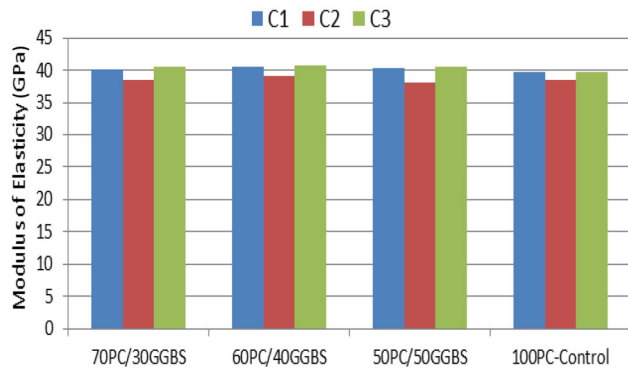


**Table 7.** The 28-day flexural strength and modulus of elasticity.

Concrete mix	Compressive cylinder strength (MPa)			Flexural strength (MPa)			Modulus of elasticity (GPa)		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
Curing conditions	C1	C2	C3	C1	C2	C3	C1	C2	C3
70PC/30GGBS	56.5	49.0	58.5	6.5	6.0	7.0	40.0	38.5	40.5
60PC/40GGBS	57.0	48.0	58.0	6.5	6.0	7.0	40.5	39.0	41.0
50PC/50GGBS	53.0	47.5	54.0	6.5	6.0	7.0	40.5	38.5	40.0
100PC-Control	56.0	55.0	57.5	6.0	6.0	7.0	39.8	38.5	39.8



**Figure 9.** Flexural strength of GGBS concrete at the age of 28 days.



**Figure 10.** Modulus of elasticity of GGBS concrete at the age of 28 days.

50GGBS concrete mixes have slightly higher flexural strength than the 100PC-Control concrete mix, which was expected according to the literature reviewed.

It is revealed from the test results that the concrete mixes, designed for equal 28 days' strength, the use of GGBS up to 50%, has slightly increased the 28 days' flexural strength in comparison to PC only concrete, which is according to the earlier research due to the better microstructure and packing of concrete [35].

**6.3a Modulus of elasticity:** From the modulus of elasticity results, it is concluded that concrete samples containing GGBS have higher values of modulus of elasticity than the PC concrete at the summer curing temperatures (20°C). The value of 28-day modulus of elasticity of concrete containing 30%, 40% and 50% GGBS are, respectively, 1%, 2% and 1.3% higher than the PC concrete mix, cured under the summer curing environment.

The winter curing environment has an adverse effect on the 28-day modulus of elasticity values of GGBS and PC concrete, similar to the compressive strength values. It is concluded that proper curing of GGBS concrete under water at 20°C or by the prevention of loss of moisture and storing at 20°C enhances the modulus of elasticity. Concrete mixes cured under water at 20°C have the higher value of modulus of elasticity than the concrete cured in sealed plastic bags at 20°C. The comparison of modulus of elasticity for GGBS concrete under various curing conditions is given in figure 10.

## 7. Conclusion

Partial replacement of cement by GGBS up to 50% has little impact on the compressive strength at 56 days, as the compressive strength achieved has a reasonable value for use in structural works. This can offer greater opportunity for saving of cement and CO<sub>2</sub> emissions, thereby making concrete relatively sustainable.

The strength development results show that at low water/cement ratio (0.35), concrete containing GGBS up to 50% gains enough high early-age strength to be used in post-tensioned concrete and fast-track construction.

The results shows that there are significant reductions in the rate of strength gain of concrete cured under winter curing conditions (7°C), as compared to those of summer curing and under water (20°C). In winter conditions, for concrete containing GGBS up to 50%, special care should be taken regarding temperature increase of the curing environment at the early age to gain enough strength. This can be achieved at covering the concrete in sealed conditions. The heating of concrete buildings to increase the temperature for curing is a common practice in cold areas.

From the compressive strength development of GGBS concrete results, it is concluded that concrete containing GGBS up to 50% has almost the same 28-day compressive strength as PC concrete, when cured under summer temperatures (20°C) and gains more strength than the PC concrete at the age of 56 days. Concrete containing 40% GGBS has the highest compressive strength compared to the other concrete mixes at the age of 56 days and is 15.5% more than the strength of PC concrete. The strength gain in GGBS concrete is more obvious between the ages of 28 and 56 days. This supported the earlier research to use 56 days' compressive strength of blended concrete.

Concrete containing GGBS up to 50% have higher values of flexural strength than the PC concrete when cured under the summer curing environment (20°C). The 28-day flexural strength of 30%, 40% and 50% GGBS concrete mixes are 3.3%, 8.2% and 4.9% higher, respectively, than the PC concrete mix cured under the summer temperature.

Curing environments have an effect on the flexural strength of GGBS concrete mixes and this is reduced after being cured under winter environments (7°C) compared to summer temperatures of 20°C in sealed plastic bags or under water. GGBS concrete and the PC concrete mixes cured under water at 20°C have higher flexural strength than the concrete cured in sealed plastic bags at 20°C.

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