STRENGTH DEVELOPMENT OF CONCRETE CONTAINING GROUND GRANULATED BLAST FURNACE SLAG FROM ARCELORMITTAL ZENICA AS A PARTIAL CEMENT REPLACEMENT

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ABSTRACT
The strength development of concrete containing ground granulated blast-furnace slag (GGBS), a by-product of iron in blast-furnace, as a partial substitute for cement,was experimentally studied. Levels of replacement of cement by slag were 12.5 %, 25 %, 37.5 %, and 50 % by weight of cement. Slag taken immediately after it was discharged from the blast furnace was used.Tests performed on concrete samples include consistency, air content, compressive strength, flexural strength, and dynamic modulus of elasticity. It was found that the addition of GGBSleads to a significant increase in the consistency of fresh concrete, a decrease in early compressive strengths and flexural strengths, as well as dynamic modulus of elasticity. At a later age, the replacement of cement with slag resulted in increasing both the modulus and strength of concrete.

1. INTRODUCTION

An increasing trend in utilizing low-carbon footprint concrete for construction has been evident over the last decades. Ground Granulated Blast-furnace Slag (GGBS) is a by-product of iron manufacturing, which is widely used as a cementitious material used in concrete. Therefore, it is of great importance to maximize the ground granulated blast furnace slag (GGBS) percentage of the total binder in structural concrete [1,2]. EN 206-1 classifies GGBS into the group of reactive mineral additions for concrete (Type II). According to this standard, additions are defined as finely divided materials used in concrete to improve certain properties or to achieve special properties [3]. General suitability as type II addition is established for GGBS conforming to EN 15167-1 [4], and, in that case, GGBS can be directly mixed with other components of a concrete mixture in concrete plants. The other way in which GGBS is used is as a component of Portland composite types of cement CEM II, CEM III, and CEM V. In that case, the standard EN 197-1 must be followed [5].

The technique of the addition incorporation into the concrete mixtures, directly or as a factory blended cement, doesn't significantly influence concrete properties. Nevertheless, the utilization of additions in concrete plants results in some benefits such as:

- transport costs reduction, because the addition can be delivered directly to the concrete plant without having to go via a cement factory,
- the possibility of more accurate proportions, because the materials are weighed in a concrete plant,
- the flexibility of proportioning and thus optimization of the technical performance of the concrete.

GGBS is typically used in the proportion of 50% of the total binder. However, it is often beneficial to be able to vary the proportion to meet specific requirements. For example, 66 to 80% GGBS is recommended for high sulfate resistance or high resistance to chloride ingress. Or, 50 to 70% GGBS may be best to reduce the heat of hydration and control the early-age cracking. Similarly, to ensure high early strength, 20 to 40% GGBS is suggested [6].

Every year, ArcelorMittal produces large amounts of a granulated blast furnace which is a by-product of the iron production process. Even though this slag has been started to sell to cement producers recently, there are still large quantities of unused slag. The conformity of this GGBS according to the standard EN 15167-1 has been proven by the authors and published elsewhere [7]. In this paper, the GGBS from ArcelorMittal Zenica was used as a partial cement replacement and added directly to the concrete mixtures. The most important properties of fresh concrete mixtures, as well as the strength and durability of hardened concrete, were investigated. As far as the authors' knowledge, such a study on this slag has not been done before.

2. EXPERIMENTAL

2.1. Materials

Ordinary Portland cement type CEM I 52.5 N was used in this study. Crushed limestone with a maximum particle size of 16 mm that complies with the requirements of EN 12620 [8] was used as aggregate in the concrete mixes. A polycarboxylate-based high-range water-reducing admixture (HRWRA) and air-entraining agent formulated from modified naturally occurring and synthetic surfactants, both conforming to EN 934-2 [9] were used as additives. GGBS produced in ArcelorMittal Zenica, conforms with EN 15167-1 [4], with a specific surface area of 4.700 cm^2/g was used as a partial cement replacement. GGBS was taken immediately after it was discharged from the blast furnace. The chemical composition of GGBS determined according to BAS EN 196-2:2013 is listed in Table 1. The most important physical properties of cement and GGBS used are listed in Table 2.

Table 1. Chemical composition of GGBS [10]

Comp	SO_3	S^{2-}	MnO	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Cl^-	Na_2O	K_2O	H_2O
%	0.41	0.64	2.64	41.05	0.83	7.79	40.62	4.88	0.003	0.22	0.82	0.04

Table 2. Physical properties of GGBS and cement CEM I [10]

Sample	Density (g/cm^3)	Specific surface area (cm^2/g)	Stand. consistency (%)	Initial setting time (min)	Soundness (mm)	Strength (MPa)			
						Flexural		Compressive	
						7 days	28 days	7 days	28 days
CEM I	3.14	3600	26.0	180	-	-	-	41.4	49.3
GGBS	2.90	4700	24.4	235	0.0	5.1	9.2	28.9	51.9

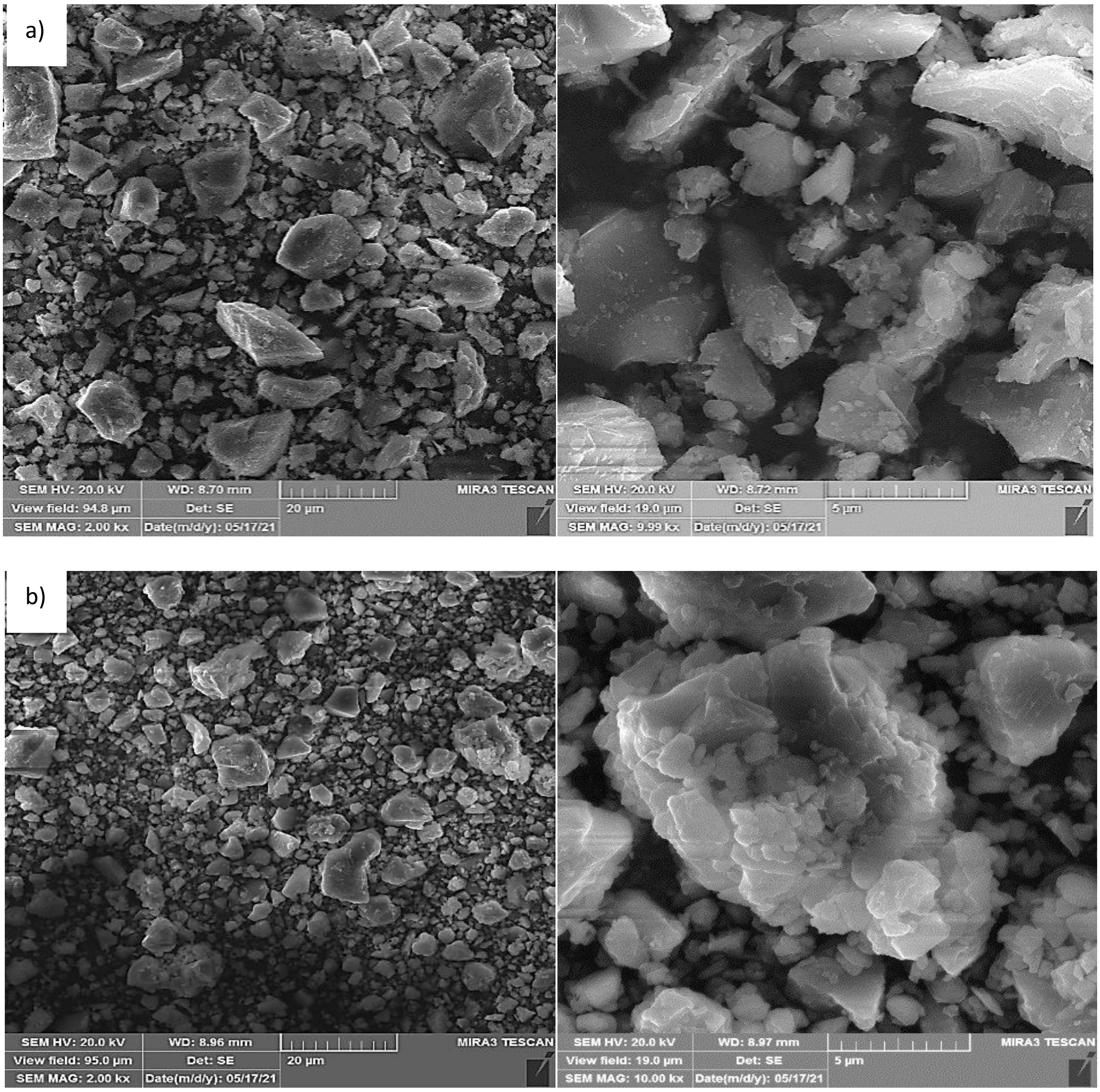

Figure 1. SEM analysis of cement (a) and GGBS (b) [10]

SEM analysis of GGBS and cement samples was carried out by scanning electron microscope Tescan Mira 3 (20keV). The micrographs presented on the left side of the image were taken at the magnification of 2000×, and the micrographs on the right side at the magnification of 10000×.

2.2. Mix proportions

Proportions of the reference mix and the mixes containing 12.5, 25.0, 37.5, and 50.0% GGBS by weight of cement are listed in Table 3.

Table 3. Mix proportion of concrete

Material		R	T-12.5	T-25	T-37.5	T-50
Cement (kg/m^3)		400	350	300	250	200
GGBS (%)		0	12.5	25.0	37.5	50.0
GGBS (kg/m^3)		-	50	100	150	200
Agreggate (kg/m^3)	0-4 mm	885	885	885	885	885
	4-8 mm	355	355	355	355	355
	8-16 mm	530	530	530	530	530
Water (kg/m^3)		176	176	176	176	176
HRWRA (kg/m^3)		3.2	3.2	3.2	3.2	3.2
Air entraining agent (kg/m^3)		0.4	0.4	0.4	0.4	0.4

2.3. Mixing procedure

First, cement and GGBS were mixed for 60 s, and after that the fine and coarse aggregates were added to the mixer, followed by dry-mixing for another 120 s. Then, around 75% of the total amount of water was added and mixed for another 120 s. Finally, the remaining mixing water and additives (HRWRA and Air entraining agent) were added to the mixer, during consecutive mixing for 180 s. The whole mixing time was 8 minutes.

2.4. Test methods

After mixing, the slump test was carried out on each mix following EN 12350-2 [11]. For testing hardened concrete properties cubes 100×100×100 mm and beams 100×100×400 mm were prepared. All specimens had been demolded after 24 hours and then stored in water at a temperature of 20 °C until tests were conducted. The compressive strength of the cubes was measured following the procedure described in the norms EN 12390-3 [12] at 2, 7, 28, 90, and 180 days. Before the compressive strength test, on cubic samples, a non-destructive test was carried out to determine the velocity of the ultrasonic pulse by direct method via a pulse velocity test device following the procedure described in the norm EN 12504-4 [13]. Dynamic modulus of elasticity is calculated according to the equation:

$$E_{bd} = \frac{V^2 \cdot \rho \cdot (1+\nu)(1-2\nu)}{(1-\nu)} \quad [Pa] \tag{1}$$

where is:
V – ultrasonic pulse velocity in m/s
ρ – apparent density in kg/m^3
ν – Poisson ratio (0.2 for concrete).

The flexural strength test was carried out on the beams according to the norm EN 12390-5 [14] at 2, 28, and 90 days.

3. RESULTS ANDDISCUSSION

The results of the slump test of fresh concrete mixes are presented in Table 4. The results show the slump of fresh concrete increases with an increasing portion of GGBS in the binder.

Table 4. Slump of concrete

Sample	R	T-12.5	T-25	T-37.5	T-50
Slump, mm)	160	160	180	210	220

The GGBS used has a greater specific surface area (SSA) than cement, and for that reason, one could expect that GGBS addition would decrease slump and have a negative effect on the concrete consistency. However, based on the slump test results, it can be concluded that the partial replacement of cement by GGBS lead to the improvement of the consistency of the concrete. This can be explained by the fact that the surface of GGBS is rather smooth, contrary to the cement particles' surface which tends to be rough. Additionally, GGBS particles are less angular and irregularly shaped than cement particles (Fig. 1). For these reasons, the water demand for binder mixes containing GGBS is generally lower than the water demand for mixes containing only cement.

Table 5. Air voids content of concrete

Sample	R	T-12.5	T-25	T-37.5	T-50
Air voids, (%)	2.9	3.2	3.1	2.8	3.4

The results listed in Table 5 show that GGBS introduction to the concrete mixes has not significantly influenced the air voids content of these mixes. The results of the compressive strength test of concrete at ages 2, 7, 28, 90, and 180 days tests are summarized in Table 6 and Figure 2.

Table 6. Compressive strength of concrete

Sample	Compressive strength [MPa]				
	2 days	7 days	28 days	90 days	180 days
R	38.9	58.3	71.6	75.7	77.4
T-12.5	35.9	56.5	70.5	80.2	83.6
T-25	29.7	52.8	69.8	84.9	88.9
T-37.5	22.9	45.7	67.2	81.0	85.1
T-50	13.7	38.2	64.0	80.6	83.8

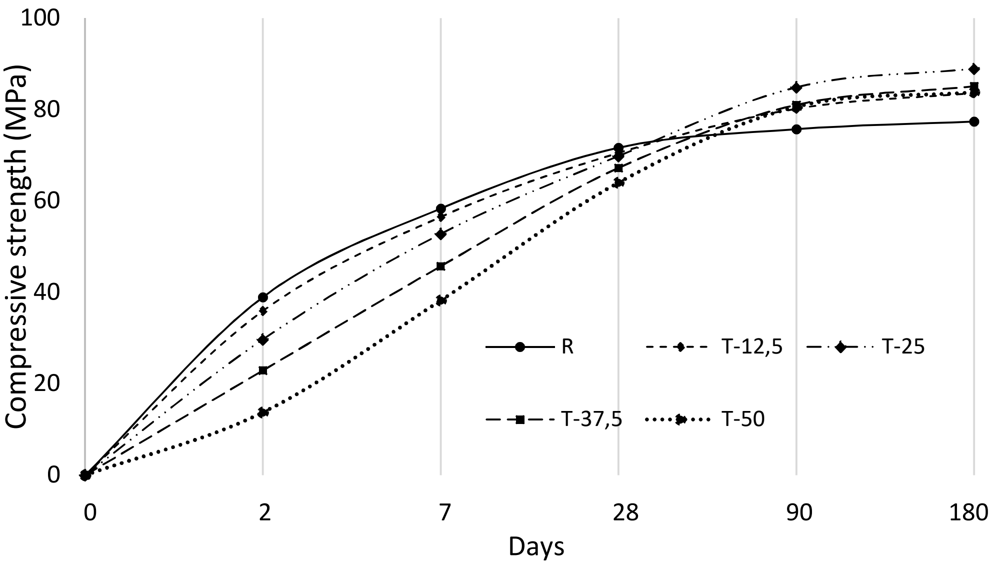

Figure 2. The development of compressive strength of concrete

Figure 2 shows that the partial replacement of cement by GGBS has the greatest effect on concrete's compressive strength at early ages (2 and 7 days). The loss in compressive strength increases with the increased content of GGBS. At the age of 28 days, concrete containing only cement as a binder (R) still has a greater compressive strength. However, at a later age (90 and 180 days) compressive strength of all concretes containing GGBS surpasses the compressive strength of the reference sample R. The greatest increase (around 15% compared to the reference sample) in compressive strength was observed in the sample containing 25 % GGBS. The results obtained are in coherence with the results published by Monteagudo [15] and Gruyaert [16].The flexural strength test results are listed in Table 7 and presented in Figure 3.

Table 7. Flexural strength of concrete

Sample	Flexural strength [MPa]		
	2 days	28 days	90 days
R	6.8	8.9	8.9
T-12.5	6.4	9.3	9.7
T-25	6.0	9.6	9.7
T-37.5	5.7	9.7	11.0
T-50	6.7	9.9	10.8

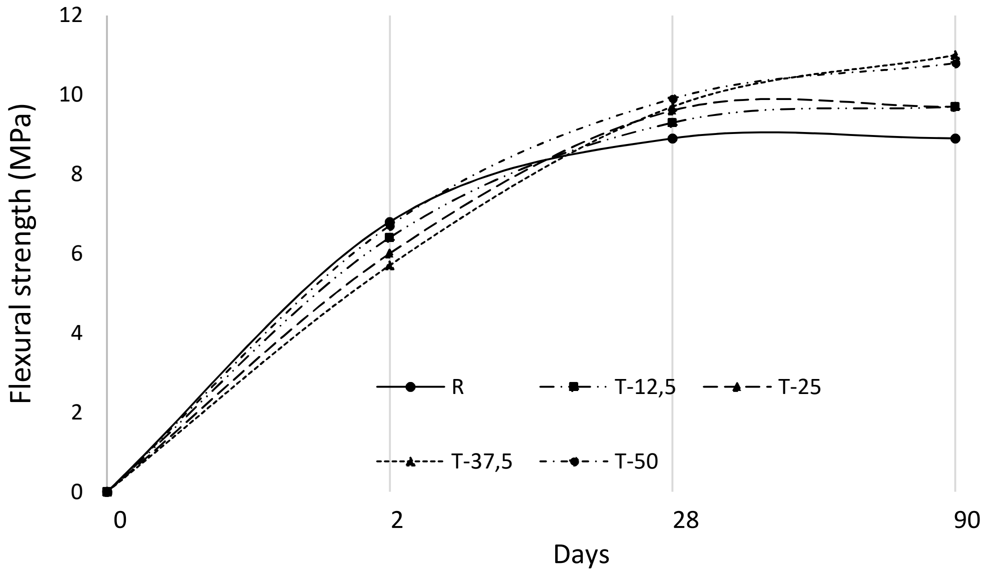

Figure 3. The development of flexural strength of concrete

The results show that, at the age of 2 days, flexural strength decreases with the increasing content of GGBS. At the ages of 28 and 90 days, all samples containing GGBS developed higher flexural strength than the reference sample. The highest flexural strength was observed in the sample with 37.5 % of GGBS, surpassing the flexural strength of the reference sample for 23.5 %. A similar trend of flexural strength development of concretes containing GGBS was observed by other authors [17].Values of dynamic modulus of elasticity calculated according to (1) are shown in Table 8 and Figure 4.

Table 8. Dynamic modulus of elasticity of concrete

Sample	Dynamic modulus of elasticity [GPa]				
	2 days	7 days	28 days	90 days	180 days
R	49.5	53.9	55.5	59.5	59.5
T-12.5	47.6	52.2	54.7	59.2	59.8
T-25	45.7	49.1	54.0	60.8	60.8
T-37.5	42.8	47.5	52.7	59.8	61.1
T-50	39.8	46.5	51.5	59.0	59.6

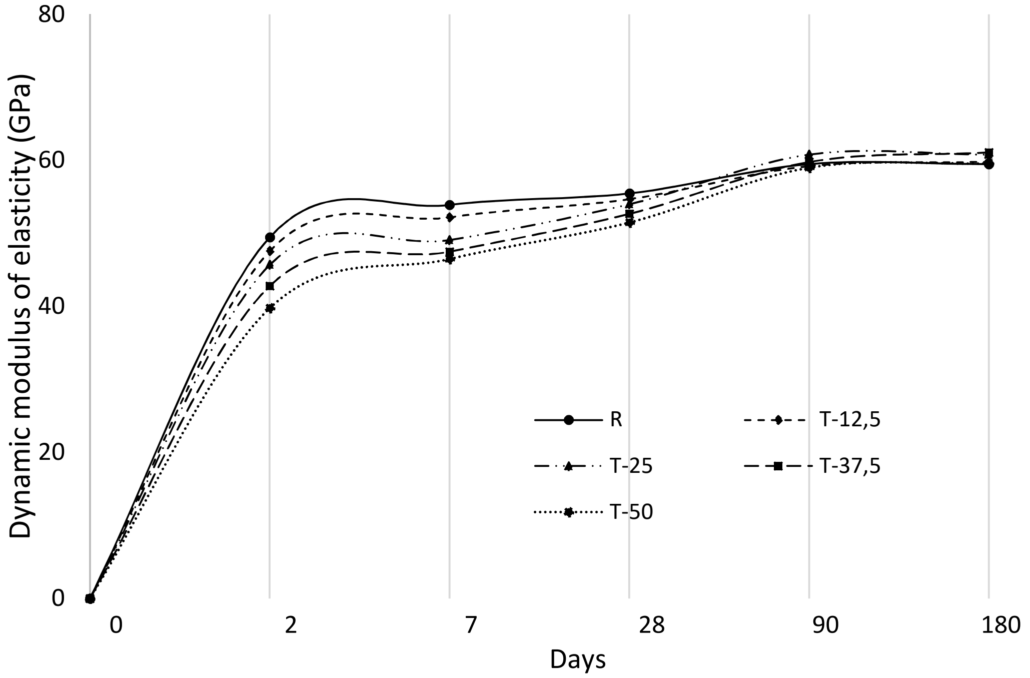

Figure 4. The development of dynamic modulus of elasticity of concrete

From the data obtained, it is evident that, at early ages, the modulus is strongly affected by the level of cement replacement. In that period, the concrete with the highest content of GGBS has the lowest value of modulus, and the modulus steadily decreases with increasing the content of GGBS in concrete. However, after 28 days these differences in values of modulus become smaller. At a later age, the modulus of concretes containing GGBS is higher than the modulus of reference concrete. These findings are in coherence with the results shown in [17].

4. CONCLUSIONS

Based on the test results, the following conclusion can be drawn:

- The replacement of cement with GGBS leads to an increase in a fresh concrete slump. The higher the level of replacement, the higher the slump.
- The air voids content has not been significantly affected by cement replacement.
- The early compressive strength showed a significant decrease at higher replacement levels, while at a later age, samples containing GGBS had greater compressive strength than samples containing only cement as a binder. The sample containing 25% GGBS developed the highest compressive strength at the age of 180 days, with an increase of 15% compared to the reference sample.

- The loss in flexural strength of samples containing GGBS was observed only at the age of 2 days. The reference sample has the lowest values of 28- and 90-day flexural strength. The samples with replacement levels of 37.5 and 50 % had the highest 28- and 90-day flexural strength.
- At an early age, the dynamic modulus of elasticity decreases with increasing the content of GGBS in concrete. At a later age, the modulus of concretes containing GGBS is higher than the modulus of reference concrete.

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