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Influence of slag powder in the cement mortar mixes on the characteristics of compactness and freeze –thaw strength

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Abstract. Worldwide, there is a clear imperativeness to reduce the consumption of non-renewable raw materials. The aim of the research is to obtain new ecological materials with applicability in the construction field, but also to efficiently manage these by-products by eliminating it completely and re-introducing it into the economic circuit. We envisaged the use of slag products as a material cementitious characteristics or as artificial aggregates, so that materials embedded in construction produce as little environmental impact as possible. After cooling, the blast furnace slag products was used in the new mortar mixes in two forms: in the form of a powder product milled from the granulated slag, and in the form of an aggregate made of non-granulated slag, sorted to the sized of 0/4 mm. Ground-granulated slag in the form of a powder below 63 μm was used as an addition to the cement mass, and the newly obtained artificial aggregate, sorted to 0/4 mm, was used in various percentages for replacing the natural aggregates in the control mix. The results show that the combined use of slag powder as an addition to the cement mass and artificial slag aggregates, regardless of the percentage of substitution of Natural aggregates in the mortar mortar mix, has led to the development of new mortar mixes with higher compaction than the control mortar. The higher filling rate due to the use of ground slag has influenced the increase of compressive strengths and freeze-thaw strengths from the repeated freeze-thaw action for new cement mortar mixes with blast furnace slag, as compared to the control mortar mix.

1. Introduction

The herein research is part of a larger experimental program taking place in the Central Materials Laboratory of the Faculty of Civil Engineering in the Technical University of Cluj-Napoca, aiming at using local by-products derived from iron smelting. Trial mixes using ground granulated blast furnace slag (GGBS) in the form of powder below 63 μm as supplement to the cement mass or ground ungranulated blast furnace slag (GUGBS) as artificial aggregates having a grain distribution of 0/4 mm and replacing Natural aggregates were investigated. Frequently, blast furnace slag (BS) contains glassy spheres as more than 95% of its mass which become a fine powder when grounded so it may be used as mineral clinker replacing part of the cement. Cement also serves as chemical catalyzer so that (BS) manifests latent hydraulic activity as well as some pozzolanic activity when reacting with the calcium hydroxide and other alkaline solutions produced by the hydration of Portland cement, see [1].



Current paper presents the influence of (GGBS) additions in mortar mixes in terms of compaction and freeze-thaw resistance, expressed as loss of compressive strength in a 150-cycle test. Values for the surface area of the cement and the GGBS powder are presented in correlation with the properties under scrutiny. Also, the properties of the Natural and artificial aggregates, the chemical composition of (GGBS) as standardized by the corresponding code provisions, as well as the actual process of extracting BS (granulated or not) during the quenching process are briefly discussed herein.

Further analysis of raw data pertinent to the materials properties, test set-ups and the data collected in the actual testing is also presented in comparison to other literature results.

2. Materials and methods

The applicable Romanian code is SR-EN 206-1, which indicates the properties to be compared when evaluating the changes induced by certain exposure conditions on the initial properties of the reference mortars. As such, the freeze-thaw resistance is critical in the evaluation of charted durability performance, see [2].

Shape, dimension, volume distribution and orientation of air bubbles impair on the permeability and gelidity properties of mortars. It is desirable therefore to create finer small voids, referred to as gel voids, which are uniformly distributed in the available volume, and to avoid the formation of capillarity voids, which have larger dimensions and may communicate to each other.

As the entrained air volume reduces the compaction increases, see [3], while other properties such as compression strength and gelidity also improve. It is deemed adequate to coin a mortar as “compact” when the overall air-entrained volume is up to 5 or 7% so a minimum compaction should be minimum 93%, see [4, 5].

Trial mixes using a GGBS ratio of 15% to replace part of the cement clinker mass and 20%, 40%, 60% and 80% of GUGBS respectively, to replace the Natural aggregates (NA) were batched. A BASF superplasticizer admixture (Ad) at a dosage of 1,2% of the cement mass was also added. The reference mix (Mc) was batched using Portland CEM I 42,5R provided by “S.C. HOLCIM Romania S.A” from the Alesd cement plant in accordance to the Romanian applicable code SR EN 197-1, while the Natural aggregates with a grading of 0/4mm were supplied from the Beclenut quarry in Bistrița-Năsăud county as allowed by the provisions of SR EN 12620:2002+A1:2007.

A summary of comparison is presented in Table 1 while Table 2 lists the corresponding aggregate properties, see [6].

Table 1. Mortars composition.

No	Abbreviated Name	Materials (g)					
		CEM I 42.5R	GGBS	NA 0/4 mm	GUGBS 0/4 mm	Water ml	Ad%
1	1.Mc	450±2		1350±5		225± 1	
	15% GGBS addition, NA substituted by 20%, 40%, 60%, 80% of GUGBS and 1.2% ad						
2	2.G3	450±2	67.5	1080±5	270±5	190± 1	1.2
3	3.G3	450±2	67.5	810±5	540±5	205± 1	1.2
4	4.G3	450±2	67.5	540±5	810±5	210± 1	1.2
5	5.G3	450±2	67.5	270±5	1080±5	215± 1	1.2

GGBS and GUGBS are both supplied by ArcelorMittal Galați from the company’s storage areas. GUGBS is the result of slow cooling the quenchants from selected molten BS, using air as conventional quenching medium.

The material is further grounded down mechanically and graded in the 0/4 mm particle size distribution in accordance with the mortars and concrete provisions indicated in SR EN 12620+A1:2008. Corresponding properties are listed in Table 3, see [7].

Table 2. Properties of Natural aggregates (NA) with a grading of 0/4 mm.

Property	Parameter
Size	D=4mm, d=0
Granulometry	G _F 85
Fines content	f ₃
Water absorption coefficient WA ₂₄ [%]	WA ₂₄ 2

Table 3. Properties of artificial aggregates (GUGBS) with a grading of 0/4 mm.

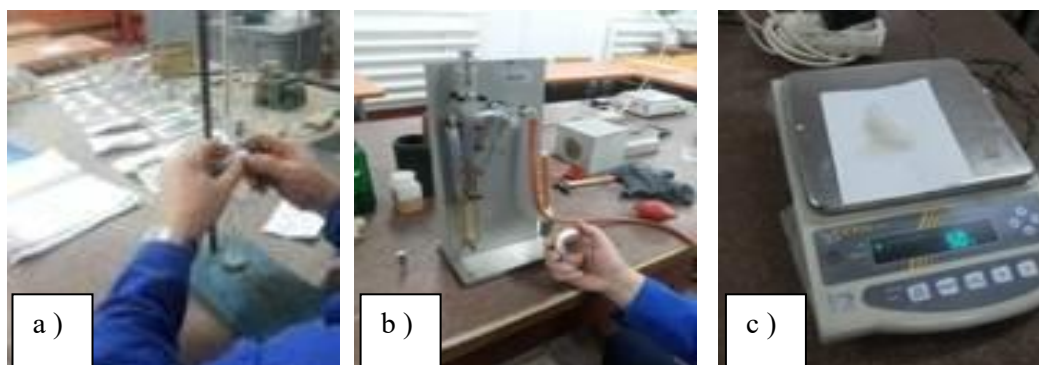
Property	Parameter
Size	D=4mm, d=0
Granulometry	G _F 85
Fines content	f ₃
Water absorption coefficient WA ₂₄ [%]	WA ₂₄ 2
Acid soluble sulphate content	AS _{0.23}
Total sulphate content	1.01

GGBS is the result of fast cooling the quenchant from selected molten BS, using water as conventional quenching medium. The material is further grounded down mechanically to a maximum grain size of 63 μm in the Alesd cement plant. In accordance to the provisions of SR EN 197-1SR EN 15167-1: 2007, the BS is expected to fulfil the following: (1) at least two thirds of its mass should be the sum of the calcium oxide (CaO) to the magnesium oxide (MgO) and the silicon dioxide (SiO₂), and (2) the mass ratio of (CaO+MgO) to (SiO₂) should be at least equal to one. The properties listed in Table 4 show that CaO+ MgO+ SiO₂ it is equal 84.05% while (CaO+MgO)/(SiO₂) it is equal 1.30 as required, see [8].

Table 4. Chemical composition of BS.

Chemical elements	SiO ₂	Al ₂ O ₃	MnO	MgO	CaO	Fe ₂ O ₃	Na ₂ O	K ₂ O
Percentage%	36.44	11.60	0.55	5.8	41.81	0.78	0.345	0.428

Figure 1 illustrates various testing stages as conducted in the current research.

**Figure 1.** a) Establishing density of hardened mortars; b) Weighting of GGBS; c) Establishing the surface area of GGBS.

The loss of compressive strength after the freeze-thaw cycle is considered a measure of degradation of the mortar samples as illustrated in Figure 2.

All samples are casted at the same age, from the same mix, and subjected to same curing conditions without any de-icing salts.



Figure 2. Testing compression strength.

Compaction is established as the ratio of the apparent density under natural moisture conditions to the dry bulk density of hardened mortar, as indicated in STAS 2414-1991 and equation (1) and is considered to represent the degree to which the apparent volume of the material is filled with solid matter.

$$C = \frac{\rho_a}{\rho} \times 100, \quad (1)$$

C – compaction of mortar (%)

ρ – dry bulk density of hardened mortar

ρ_a – apparent density of hardened mortar

The dry bulk density of hardened mortar is calculated by the pycnometer test as the ratio of the sample's powdered mass to the difference in volume of the flask and the spare distilled water that leaks, for a stated temperature, as in equation (2).

$$\rho = \frac{m}{V_b - V_s}, \quad (2)$$

ρ – dry bulk density of hardened mortar [g/cm³]

m – powdered mass of sample (equal to 5g)

V_b – volume of flask (equal to 25 cm³)

V_s – volume of leaking spare distilled water

The apparent density of hardened mortar is calculated as the ratio of the sample's dry mass to the apparent volume as per SR-EN 1015-10/2002 and SR-EN 1015-10/A1/2007. The surface area of the cement and BS powder is calculated by the Blaine permeability tester as in equation (3), see [5,9].

$$S = K \cdot \frac{\sqrt{n^3}}{\rho} \cdot \frac{\sqrt{tc}}{(1-n)} \cdot \frac{1}{\sqrt{\eta}}, \quad (3)$$

S – surface area [cm²/g]

K – the apparatus constant

n – porosity of the bed

t_c – measured time

ρ – density of material

η – viscosity of air at the test temperature

Freeze-thaw is expressed as the number of successive cycles that samples resisted with a loss of compressive strength of up to 25% versus the reference specimens, which are cured in water as indicated in SR 3518-2009, see equation (4).

$$\eta = \frac{f_{cm} - f_c}{f_{cm}} \cdot 100, \quad (4)$$

η – compressive strength loss

f_{cm} – mean compressive strength on reference specimens [MPa]

f_c – mean compressive strength of samples subjected to free-thaw cycles [MPa].

3. Results

A summary of comparison of mortar specimens is presented in Table 5. Reference samples were tested at 7 and 28 days to investigate their increase in strength and to provide a base for comparison for the free-thaw samples. The surface area of cement is 4385 cm²/g while for BS the corresponding value is 5770 cm²/g, was determined in laboratory, see [6].

Table 5. Compressive strength development, loss of strength after the 150 freeze-thaw cycle, compaction of mortar specimens.

Mix Name/proportions	Abbreviation	fc at 7 days (MPa)	fc at 28days (MPa)	fc of reference samples for freeze-thaw testing (MPa)	fc after 150 freeze-thaw cycles (MPa)	Loss of compressive strength (%)	f_{cG3}/f_{cMc} at 7 days (%)	f_{cG3}/f_{cMc} at 28 days (%)	Compaction (%)
Reference mortar	1Mc	34.48	51.55	43.33	39.75	9.01	-	-	92.95
15% GGBS addition, NA substituted by 20%, 40%, 60%, 80% of GUGBS and 1.2% ad									
15%_20%_1.2%	2G3	63.97	71.59	78.93	76.22	3.44	1.86	1.39	95.08
15%_40%_1.2%	3G3	62.06	72.23	78.59	75.30	4.19	1.80	1.40	94.80
15%_60%_1.2%	4G3	63.57	75.92	79.67	75.65	5.05	1.84	1.47	93.28
15%_80%_1.2%	5G3	63.96	70.19	79.55	78.54	1.27	1.85	1.36	93.97

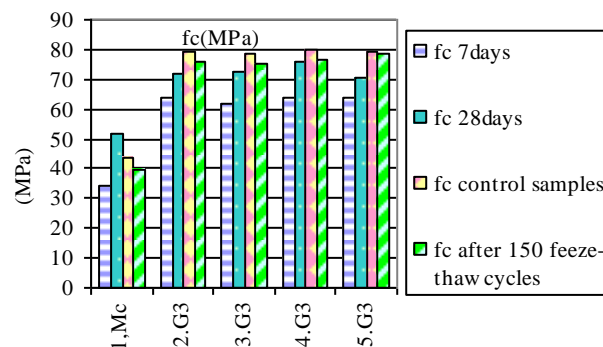
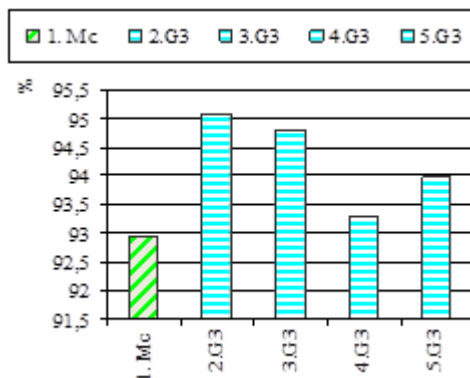
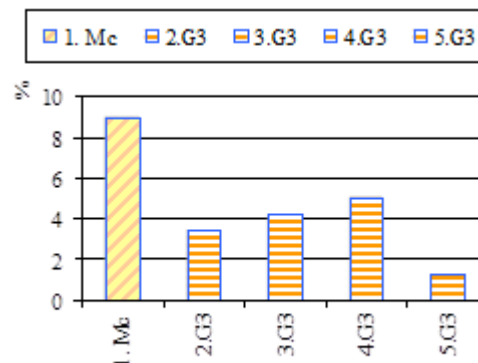


Figure 3. Compressive strength.

**Figure 4.** Compactly on mortar mixtures.**Figure 5.** Loss of compressive strength after 150cycles.

As supported by the data in Table 5, there is a significant difference in-between the trial mixes and the reference mix. Figure 3 illustrates the development of the compressive strength at 7 days, at 28 days and for the reference mix samples fully submerged in water versus the same properties for the trial mixes subjected to 150 freeze-thaw cycles in the thermostatic test chamber. It may also be concluded that freeze-thaw had little detrimental effect on the trial mixes since, as in Figure 4, compaction ratio is above 93% regardless of the ratio of substituting the natural aggregates and, as in Figure 5, the loss of compressive strength is below that recorded for the reference mix

4. Discussions

Results summarized in Table 5 indicate that at the age of 7 day the compressive strength of reference samples is about 67% of the strength at 28 days which is below the 81-89 % ratio for the trial mixes. As suggested in [10] mixes with rapid-hardening Portland cement may reach at 7 days about 75% of the strength at 28 days, a similar magnitude being recorded in the present investigation. Trial mixes show an increase of the compressive strength of more than 80% at 7 days and more than 36% at 28 days, see f_{cG3}/f_{cMc} ratio in Table 5. A possible cause may be the greater surface area of the BS powder, 5770 cm²/g, as compared with the cement clinker, 4385 cm²/g, also see [11-13]. Other positive effects include a lower volume of voids for a greater fineness of the blended aggregates, lower porosity and better compaction as compared with the reference mix. The superplasticizer admixture contributed by increasing the workability of the mix while decreasing the W/C ratio and therefore creating higher strengths. BS is a cementitious constituent that manifests latent hydraulic activity as well as some pozzolanic activity that improves properties of the fresh and hardened mix. The fresh properties include better rheology, stiffening, workability and improved finishing possibilities, while the hardened properties translate to higher mechanical strengths and durability, see [14].

5. Conclusions

Current paper presents the influence of various ratios of BS additions to mortars, in terms of compaction and freeze-thaw resistance. Results indicate that the mixed use, both as grounded powder and artificial aggregates regardless of the substitution ratio, place the trial mixes above the reference mix in terms of performance.

Using BS as cement addition in combination with a greater surface area of the finer cementitious powder creates better compaction, superior mechanical performance and increased durability.

Since BS is a by-product of selected industrial processes, any reuse of such products decreases storage areas and reduces the carbon footprint of cement, for it is already established that one tonne of

cement generates a similar quantity of Carbon Dioxide, see [15]. A better management of by-products creates indirect economic advantages as well as superior quality readily available concrete products.

Replacing Natural aggregates with artificially created BS substitutes reduces the extraction of non-renewable materials and generates sustainability [16-18].

The main purpose of the current experimental programme is the development of new BS interblended with cement mortars that may be used as durable and sustainable concrete pavements.

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