Properties of self-compacting mortar containing nano blast furnace slag

Prof. Dr. Alaa Ab Atiyah¹, Prof. Dr. Shakir A Salih² and Ahmed S Kadhim³

¹ Materials Engineering Department, University of Technology, Iraq – Baghdad
² Civil Engineering Department, University of Technology, Iraq – Baghdad
³ PhD Student, Materials Engineering Department, University of Technology, Iraq – Baghdad

Email: 130035@uotechnology.edu.iq.com

Abstract. In this research, an experimental study of the properties of self-compacting mortar with Nano blast furnace slag has been done. Nano blast furnace slag was prepared and used as an additive to the self-compacting mortar in (1, 2, 3, 4, 5) % by weights cementitious sustainable materials. Blast furnace slag was crushed and milled until achieving to Nano particle size, Nano particle size was provided and checked by Laser Particle Size Analysis, AFM, and FESEM. Self-compacting mortar was tested at 7, 28, and 90 days’ age. Fresh properties of self-compacting mortar were determined by using mini flow table test and mini v-funnel test. The experimental results of self-compacting mortar shown that the mechanical properties include compressive strength, flexural strength, and direct tensile strength were increased as Nano powder percentage increases. The physical properties such as total water absorption and porosity was decreased as a Nano powder percentage was increased. While the density of self-compacting mortar increased as Nano powder percentage increase. The microstructure homogeneity and Nano powder distributions of self-compacting mortar were explained by using FESEM.

1. Introduction
Concrete is widely used building materials, it is predominantly depended upon the conduct of its constitutes compounds like mortar, aggregate, and aggregate – paste interface. Consequently, various studies have been taken to enhance the conduct of cement paste and mortar [1]. Pozzolanic materials were totted up in cement paste and mortar to improve its mechanical and durability properties with dense microstructure. Previous studies explain that the silica fume is quite effective to enhance mortar and cement properties by increase in rate of cement hydration. Furthermore, effectiveness of cement paste and mortar was developed to reduce quantity of Ca(OH)₂(CH) crystals and strengthening of aggregate, cement past interfacial zone by filling the minute pores present in it [2,3]. Otherwise, metakaolin and ground granulated blast furnace slag (GGBFS) would be able to advancement of cement paste and mortar behaviors [4,5]. These materials provided a probability to decrease the consuming of the cement and assisted to advanced sustainable building material. GBFS is often used after additional processing through drying and then milling to an ultrafine powders. GBFS could be utilized as a direct replacement for cement with varying replacement ratio between 30% and 85% [6]. Suresh et al. described that compressive strength enhancement of slag concrete after 28 days age is better than that concrete without GGBFS, and is less permeable concrete by decrease the pore size and densify the microstructure as compared to normal concrete. High GGBFS percentage replacement may give denser microstructure and restrict water penetration into concrete [7]. Lim et al. indicate lower compressive strength at early ages of self-compacting mortar when combined with GGBFS. The compressive strength developed with time and became better obviously at 30 – 50% quantity replacement. Consequently, to produce the
excellent development of compressive strength, the maximum limitation of GGBFS replacement ratio was referenced be remaining at 50% [8]. Teng et al. clarify that the very fine GGBFS powders has a greatest effects on the flexural strength of the concrete with low water–cement ratio [9].

Self-compacting mortars as new engineering products; are utilized to the rehabilitation and repairing of reinforced concrete. The water-cementitious materials ratio and type of chemical admixture should be specified carefully for mixtures to bring on fresh mortar without any vibration and without any segregation and bleeding. Furthermore, the self-compaction of mortar may give considerable advantages over the normal mortar on decreasing the construction time and improvement in filling ability of reinforced concrete structures [10]. High cement content is needed in self-compacting mortars to improve their flowability and stability, and inert fillers and supplementary cementitious materials can be used for this purpose [11]. The applications of nanotechnology have gained popularity in the different fields of science, technology and building materials. Nanoparticles can enhance the mechanical strength of cementitious materials [12, 13]. The self-compaction has been identified as the capability of the fresh concrete mix to fall under its own weight however kept of sufficient homogeneity without any segregation and bleeding [12,10].

The objective of this study is to investigate the influence of Nano blast furnace slag used as additives by weight of cementitious materials in the fresh state and hard state properties of self-compacting mortar.

2. Experimental program

The cementitious materials used to produce self-compacting mortar were Ordinary Portland Cement (OPC) Type I, sand, micro silica powder (MS), Nano blast furnace slag (GBFS), and super plasticizer.

2.1. Cement

The chemical and physical properties as shown in table 1 and table 2 of the cement used in this research was compatible with limitation in ASTM C150-04 [14].

| Table 1. Physical properties of Portland cement. |
|-----------------------------------------------|
| Physical properties                          | Results | Limits of ASTM |
| Specific surface (m²/kg)                     | 395     |                |
| Setting time (Vicat’s method)                |         |                |
| -Initial setting (min)                       | 90      | ≥ 45           |
| -Final setting (min)                         | 210     | ≤ 375          |
| Compressive strength of Mortar (MPa)         |         |                |
| 3-days                                       | 20.3    | ≥ 12           |
| 7-days                                       | 30.1    | ≥ 19           |
| Expansion (Autoclave), Max,%                 | 0.05    | ≤ 0.8          |
| L.O.I. Max,%                                 | 2.16    | 3              |
| L.S.F. %                                     | 0.88    |                |
| I.R. Max,%                                   | 0.36    | 0.75           |
Table 2. Chemical components of Portland cement and Nano blast furnace slag.

| Components        | Cement Type I [Wt. %] | Nano blast furnace slag [wt. %] |
|-------------------|------------------------|---------------------------------|
| CaO               | 61.11                  | 1.16                           |
| SiO₂              | 20.38                  | 67.95                          |
| Al₂O₃             | 5.82                   | 20.75                          |
| Fe₂O₃             | 3.28                   | 3.5                            |
| MgO               | 4.27                   | /                              |
| MnO               | /                      | 5.2                            |
| SO₃               | 2.12                   | 0.01                           |
| Other oxides      | /                      | 1.3                            |

2.2. Aggregate
For self-compacting mortar mixes, cement and natural river sand with a maximum size of 4.75 mm was mixed with the ratio 1:2 by wt. The specific gravity of sand is 2.65, the fineness modulus is 2.61, the sulfate content is 0.086 %, Clays and Fine material is 2.9 %, and absorption capacity was 1.75%. The grading of sand was as per the ASTM C33 specification [15].

2.3. Micro silica
Densified micro silica produced by BASF Company was used as Pozzolanic admixture; the characteristic of micro silica conforms to the requirement of ASTM C-1240-05 [16], where the specific gravity equals to 2300 kg/m³, SiO₂ more than 85%, SO₃ less than 2%, Finesse larger than 15000 m²/kg, and the activity index is 147%.

2.4. Superplasticizer
High range water reducer admixture superplasticizer based on modified polycarboxylic ether manufactured by BASF Company with relative density of 1.07, conforming to ASTM C-494 type F&G [17] was incorporated into all mixes. The contents were controlled for mixes to ensure no segregation and good workability.

3. Preparation of Nano blast furnace slag
The blast furnace slag is an industrial by-product of iron and steel industry. Blast furnace slag was prepared through two stage. In the first stage, blast furnace slag was crushed by jaw crusher to produce small particle size powder, and then the sieved products to prepare it to the next stage. In the Second stage, crushed slag powder was milled by the stainless-steel ball mill. The duration of the milling process was about five hours for one kilogram of slag as shown in ‘Figure 1’. Atomic force microscopy (AFM), laser particle size analysis, and field emission scanning electron microscope processes, tests were used to assess the Nano particle size of slag powder. The results as shown in ‘Figure 2’, illustrates the nanoparticle scale achieved. AFM test gives 63.21 nm as the average diameter, while the laser particle size analysis gives the effective diameter as 67.5 nm. FESEM gives the nanoparticle size, scale and the shape of slag powder particles. The activity index results of blast furnace slag was equal to 100% at 7 days, and 119% at 28 days, so that it is classified as Grade 120 according to ASTM C989 – 04 [18]. The chemical analysis was illustrated by EDS analysis as shown in table 2.
Figure 1. The particle size analysis with milling processing time.

Figure 2. Particle size analysis of Nano Blast Furnace Slag: (A) Laser particle size analysis done in the Nano Technology Center at the University of Technology – Baghdad- Iraq, (B) Atomic force microscopy AFM was done at the University of Baghdad – Baghdad- Iraq, and (C) field emission scanning electron microscope FESEM was done in the Razi Metallurgical Research Center – Tehran – Iran.
4. Mixture proportion
Details of mix proportions for self-compacting mortars including nano blast furnace slag (GBFS) powder are given in Table 3. The water cementitious ratio (W/CM) was 0.35, and five content with the Nano slag powder addition by weight of cement were adopted. In all mixtures, the amount of superplasticizer used was sufficient such that no segregation no bleeding was reported. Mix proportion with some modification conforms to research [19].

Table 3. Mix proportions of self-compacting mortar containing nano blast furnace slag

| Mix proportions | Cement (kg/m³) | Sand (kg/m³) | Micro silica (kg/m³) | W/CM wt.% ratio | S/CM wt.% ratio |
|-----------------|----------------|--------------|---------------------|-----------------|-----------------|
| Mix ID          | Ref. mix       | NCIS1        | NCIS2               | NCIS3           | NCIS4           | NCIS5           |
| Nano slag %     | 0              | 1            | 2                   | 3               | 4               | 5               |

5. Tests method
The experimental study comprised of two stages are first stage, flow diameter, V- funnel flow tests as conducted to assess the workability of the mix, and second stage, physical and mechanical properties of self-compacting mortar as determined. Specimens were cured into water tank at a temperature of (23±2°C) till test age.

5.1. Fresh mortar tests

5.1.1. Mini slump. The apparatus for slump flow of mortar consists of a mold in the form of cone, 60 mm high with 70 mm diameter at the top and 100 at the base. The cone was placed at the center of steel based plate and was filled with mortar. Immediately after filling, the cone was lifted; the mortar spreads without any segregation and bleeding over the table and the average diameter of speared measured. This test according to EFNARC 2005 [20], ASTM C1437 – 03 [21], and ASTM C230M-03 [22].

5.1.2. Mini V-Funnel flow. This test was used to select a suitable water powder ratio in the mix design, the funnel was filled with mortar; the gate was then unlocked and stopwatch simultaneously started. The watch was paused when the light first appeared; looking down into the funnel from above, the flow time (in Sec.) was then recorded, according to the procedure outlined in EFNARC 2005 [20].

5.2. Hardened mortar tests

5.2.1. Mechanical properties. After the completion of initial fresh mortar tests, mixtures were poured into; cubic steel mold (50 mm³) for the compressive strength according to ASTM C109/C109M-12[23], prisms steel mold (40 x 40 x 160) mm for flexural strength according to ASTM C348 [24], and briquette mold for direct tensile strength according to ASTM C190 – 85 [25]. Self-compacting mortar was tested at 7, 28, and 90 days.

5.2.2. Physical properties. Dry density, total absorption, and total porosity properties of self-compacting mortar were experimentally determined according to ASTM C642 – 13 [26].

6. Results and discussions

6.1. Fresh properties
Mini slump and mini v-funnel tests results of self-compacting mortar have been shown in table 4. The results reflecting the viscosity and segregation resistance of mortar mixtures. Slump flow diameters of all mixtures were kept in the range of (250 – 300 mm) and flowability in the range between (7-14 Sec.). Thus, fresh mixtures had some workability properties that conformed to the EFNARC [20] recommendation. Furthermore, the flowability of the self-compacting mortar was estimated via mini v-funnel, which was based on the time of the mortar mixture required to flow through the funnel. As clarified in the results, it is known that increasing the surface area of materials such as nano blast furnace slag would be needed to increase the flow diameter and reduces flow time of mortar mixes, this gives more filling ability and flowability of mortar.

| Mix ID | Ref.Mix | NCIS1 | NCIS2 | NCIS3 | NCIS4 | NCIS5 |
|--------|---------|-------|-------|-------|-------|-------|
| Mini-Slump Test (mm) | 259.17 | 275.85 | 280.82 | 282.67 | 284.32 | 290.20 |
| V-Funnel Test (sec.) | 13 | 11.5 | 10 | 9.5 | 8.5 | 7.5 |

6.2. Physical properties

Physical properties tests such as dry density, water absorption, and total porosity of self-compacting mortar were carried out in 7, 28, 90 days age. As shown in ‘Figure 3’, the dry density of hardened mortar results, increase with the addition of nanoparticles slag powder and densified with curing time as compared to reference mix. Nano slag could be effectively used as a filler to decrease the pore size and cumulative pore volume, leading to more impermeable mortar. While, the water absorption as shown in ‘Figure 4’, indicated that the mortar absorption decrease as nanoparticles slag additives increased. Also the results of total porosity as shown in ‘Figure 5’, explained that microporous of mortar were reduced when the additives of nanoparticles slag rise, hence it reduces the total porosity.

![Figure 3. The development of dry density of self-compacting mortar with addition Nano blast furnace slag.](image-url)
6.3. Mechanical properties
The mechanical properties i.e. compressive strength, direct tensile strength, and flexural strength of self-compacting mortar developed by addition of nanoparticle slag powder. The results ‘Figure 6’ showed that the compressive strength develops with the addition of nano blast furnace slag powder as compared to reference self-compacting mortar mix specimen. The compressive strength increases with the increases of the nanoparticle slag powder content for all curing ages 7, 28, 90 days. Also, it is found that the direct tensile strength ‘Figure 7’ and the flexural strength ‘Figure 8’ improved with the addition of nanoparticle slag powder for all curing ages 7, 28 and 90 days. The mechanical properties enhancement of the cement mortar composite due to the use of nanoparticles was observed by others [27]. These studies have shown that the high chemical reactivity of nanoparticles is advantageous to originate additional nucleation places in order to produce more C-S-H phases, which have an effect on concrete strength. In the case of Nano blast furnace slag which containing mixture of SiO₂, Al₂O₃, and other oxides, the Pozzolanic effect could be also considered. Nano – additives, due to their ultrafine particle size, nature, have the ability to increase packing density of the mix. In addition, the chemical reaction between the siliceous nanoparticles and calcium hydroxide, lead to produce more C-S-H in microstructure. Worst mechanical properties may be related to the agglomeration of nanoparticles and formation of the weaker areas within the hydrated binder matrix [27].

![Figure 6](image6.png)

**Figure 6.** The development of compressive strength of self-compacting mortar with addition Nano blast furnace slag.
6.4. Microstructure
The homogenoussity of the hardened mortar microstructure was observed by field emission scanning electron microscope analysis. Nanoparticles slag powder acts as filling of the porosity and voids in self-compacting mortar. Also, the distribution and agglomerations of nanoparticle slag powder inside the microstructure of mortar was noticed. As shown in ‘Figure 9’, self-compacting mortar that consists of nano blast furnace slag powders exhibited less porous with smaller pore size and densified microstructure as compare to reference mortar. The presence of blast furnace slag and Portland cement both hydrate together with water and tends to form calcium silicate hydrates. Additionally, the nanoparticles powder would react with excess of calcium hydroxide to form a finely dispersed gel that fill the large pores, as a result of that; the hardened cement paste contains less calcium hydroxide crystal and therefore has little large capillary pores [28].
7. Conclusion
Based on the test results of this study the following conclusion could be drawn:

1- The nano blast furnace slag powder has a pozzolanic activity when used as additional powder to conventional cement mortar.

2- The addition of blast furnace slag powder to mortar mixes leads to:
   a- Increase in dry density by about (0.16% to 1.43%) for mortar at 28 days age.
   b- Decrease in water absorption and total porosity by about (32.55% to 45.75%) and (9.9% to 55.2%) respectively.
   c- Increase in compressive strength, direct tensile strength, and flexural strength by about (12.32% to 59.40%), (7.94% to 38.98%), and (9.4% to 22.83%) respectively as compared to conventional reference mortar at 28 days age.
   d- Densified the microstructure of the matrix.

Acknowledgments
This studying was carried out at Civil Engineering Department and Materials Engineering Department laboratories – University of Technology – Baghdad – Iraq.

References
[1] Neville A 2006 Concrete Thomas telford ltd 1 Heron Quay London E14 4JD 1 – 321
[2] Rao G A 2003 Investigations on the performance of silica fume-incorporated cement pastes and mortars Cem. Conc. Resear. 33 pp 1765 – 70
[3] Rao G A 2001 Development of strength with age of mortars containing silica fume Cem. Conc. Resear. 31 pp 1141 – 46
[4] Kadri E H, Kenai S, Ezziane K, Siddique R and De Schutter G 2011 Influence of metakaolin and silica fume on the heat of hydration and compressive strength development of mortar Appl. Clay Scien. 53 pp 704 – 08
[5] Li K, Zeng Q, Luo M and Pang X 2014 Effect of self-desiccation on the pore structure of paste and mortar incorporating 70% GGBS Const. Build. Mater. 51 pp 329 – 37
[6] Isa Yuksel 2018 Waste and Supplementary Cementitious Materials in Concrete Elsevier ltd. 361 –15
[7] Suresh D and Nagaraju K 2015 Ground granulated blast furnace slag (GGBS) in concrete – a review. IOSR J. Mech. Civil Eng. 12 76 –82
[8] Lim S, Ling T and Hussin M 2012 Strength properties of self-compacting mortar mixed with GGBFS. Proc. Inst. Civil Eng. Construct. Mater. 165 pp 87 –98
[9] Teng S, Lim T and Sabet D B 2013 Durability and mechanical properties of high strength concrete incorporating ultra-fine ground granulated blast-furnace slag. Constr. Build. Mater. 40 pp 875 –81
[10] Turk K 2012 Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume. Constr. Build. Mater. 37 pp 326 –334
[11] Benabed B, Kadri E H, Azzouz L and Kenai S 2012 Properties of self-compacting mortar made with various types of sand Cem. Conc. Comp. 34 pp 1167–73
[12] Sanchez F and Sobolev K 2010 Nanotechnology in concrete – review Constr. Build. Mater. 24 pp 2060 –71
[13] Shih J Y, Chang T P and Hsiao T C 2006 Effect of nanosilica on characterization of Portland cement composite Mater. Sci. Eng. A 424 pp 266 –274
[14] ASTM C150 – 04 2004 Standard specification for portland cement ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –8
[15] ASTM C33 – 03 2004 Standard specification for concrete aggregates ASTM International 100 barr harbor West Conshohocken United States pp 1 –11
[16] ASTM C1240 – 07 2007 Standard specification for the use of silica fume as a mineral admixture in hydraulic cement concrete, mortar and grout ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –7
[17] ASTM C494/C494M – 05a 2005 Standard specification for chemical admixtures for concrete ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –9
[18] ASTM C989 – 04 2004 Standard specification for ground granulated blast-furnace slag for use in concrete and mortars ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –5
[19] Uygunoglu T and Topcu I B 2010 The role of scrap rubber particles on the drying shrinkage and mechanical properties of self-consolidating mortars Const. Build. Mater. 24 pp 1141 –150
[20] The european guidelines for self-compacting concrete EFNARC 2005 pp 1 –68
[21] ASTM C1437 – 03 2005 Standard test method for flow of hydraulic cement mortar ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –2
[22] ASTM C230/C230M – 03 2005 Standard specification for flow table for use in tests of hydraulic cement ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –7
[23] ASTM C109/C109M – 05 2005 Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens) ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –9
[24] ASTM C348 – 02 2005 Standard test method for flexural strength of hydraulic cement mortars ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –6
[25] ASTM C190 – 85 2005 Standard specification for tensile strength of hydraulic cement mortars ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –5
[26] ASTM C642 – 13 2005 Standard test method for density, absorption, and voids in hardened concrete ASTM International 100 Barr Harbor West Conshohocken United States pp 1 –3
[27] Li H, Xiao H G, Yuan J and Ou J 2004 Microstructure of cement mortar with nano-particles composite part B 35 pp 185 –189
[28] Sabdono P, Sustiawan F and Fadillalah D A 2014 The effect of nano-cement content to the compressive strength of mortar Proce. Engin. 95 pp 386 –95