Thermomechanical and morphological properties of sustainable mortars employing blast furnace slag and fly ash reinforced cement

I Farina¹, R Singh²,³, M Singh², P Preet², R Kumar⁴, F Fraternali⁵ and F Colangelo¹

¹Dept. of Engineering, University of Naples (Italy)
²Dept. of Production Engineering, Guru Nanak Dev Eng. College, Ludhiana (India)
³Dept. of Mechanical Engineering, National Institute of Technical Teachers Training and Research, Chandigarh (India)
⁴University Centre for Research and Development, Chandigarh University, Mohali (India)
⁵Dept. of Civil Engineering, University of Salerno (Italy)

Email: ilenia.farina@uniparthenope.it; rupindersingh78@yahoo.com; ms.hps1@gmail.com; pawankumar200708@gmail.com; ranvijayk12@gmail.com; f.fraternali@unisa.it; francesco.colangelo@uniparthenope.it

Abstract. The blast furnace slag (BFS) is non-metallic co-product (such as silicates and alumina silicates etc.) which absorbs sulphur from the charge and comprises of around 20% (by weight) of Fe production and its use as reinforcement in cement mortar has been widely explored to improve thermal and compressive properties along with addressing the sustainability issues related to Fe production. But hitherto little has been reported on effect of BFS and fly ash (FA) reinforced cement mortar from surface topography, thermal stability and morphological properties view point. This paper reports the comparison of compressive, thermal and morphological properties of cement mortar with air cooled BFS and FA reinforced cement mortar as a case study. The results of study suggests that 80% of BFS and 20% FA reinforced cement mortar (cement: (BFS+FA): 1: (0.8+0.2) by weight%) possess lowest thermal conductivity (0.65W/mK), greatest porosity (29.65%) and acceptable compressive strength (6.6MPa) in comparison to cement mortar comprising of cement: sand as 1:1. The results are supported with compressive strength data, optical photo micrographs, thermal analysis based upon differential scanning calorimetry (DSC), surface topography (based upon 3D rendered images).

1. Introduction

Recycling of industrial and agricultural solid waste is one of the suitable solutions for minimizing pollution as well as economic issues [1]. Waste materials such as FA, fuel waste, fluxing waste and plastic can be used for the production of bricks to reduce the pollutants [2] and for the production of sustainable materials [3]. To safeguard the environment, recycling of solid waste plays a vital role. Presently around 960 million Tons of waste is present in terms of industrial, agricultural and mining waste and re-use of these waste substances can help significantly to reduce the environmental pollution [4-7]. The use of these types of waste in civil construction may reduce the weight of concrete structures. It has been reported that thermal conductivity (k) is lower in light weight concrete in comparison to normal weight concrete which results in reduction of heat transfer and energy consumption [8]. Some studies have reported application of wool fibers in cement mortar panels and investigations for...
mechanical strength and insulation properties were made [9]. It has been observed that the use of wheat and barley straw as fiber reinforcement for unfired bricks resulted into decreases in thermal conductivity, while it increased with use of higher cement and gypsum content [10]. Application of FA and bottom ash separately in different proportions resulted into reduction of ‘k’ value of building material, thus increasing the energy efficiency and saving the natural mineral sand [11-12].

Use of boron active belite cement mortar with addition of FA in different combinations/proportions increased the compressive strength of mortar at high temperature and significantly improved the high temperature resistance [13]. To study the effect of FA and lime on transport performance and mechanical properties of cement mortar and its application in filling material to improve the strength of filling body has been explored by some researchers [14]. In order to understand the impact of fineness and replacement ratio of FA in different combinations resulting in increase of compressive strength and lowering water absorption and decrease of porosity in blended cement mortar, studies have been widely reported [15-16]. Also significant studies have been reported on application of recycled waste glass powder of ground granulated BFS or FA cement binder blend to investigate micro-structural properties which shows improved compressive strength with lower total porosity and exhibit a dense microstructure [17]. Some studies have reported that morphology of the matrix is more relevant to thermal conductivity of mortars as compared to chemical composition of its components. As regards to strength of mortars containing ground granulated BFS along with Portland cement reveals that mortars attain strength fast at high temperature and curing temperature significantly affect the ultimate strength [18]. In case of low and high exposure temperatures (i.e. up to 250 and 500 °C or greater), BFS can effectively improve the mortar’s performance. The literature review reveals that significant studies have been reported on use of BFS and FA as reinforcement in cement. But hitherto little has been reported on effect of BFS and FA reinforced cement mortar from surface topography, thermal stability and morphological properties view point. This paper reports the comparison of compressive, thermal and morphological properties of cement mortar with air cooled BFS and FA reinforced cement mortar as a case study. The BFS has been procured from local industry in Naples (Italy) and cast of different proportions were prepared (11×11×3cm) after blending with cement.

2. Experimentation
Blast furnace slag and marble sludge were used as sand replacement at different percentages (0%, 40%+60%, 60%+40%, 80%+20%) by weight while fly ash were used as 20% (by weight) cement replacement (table 1). Samples having dimension of 11×11×3 cm were casted and cured for 28 days at room temperature.

| No. | Nomenclature | Material composition | Material composition in ratio’s |
|-----|--------------|----------------------|--------------------------------|
| 1   | REF 1        | Cement mortar using 100% sand as aggregate | C:S 1:1 |
|     | REF 2        |                      |                                |
| 2   | BFS40-1      | Cement mortar using 20% FA (by wt.%) as replacement of cement and 40% BFS and 60% MS (by wt.%) as replacement of sand | C:(BFS+MS) 1:(0.4+0.6) |
|     | BFS40-2      |                      |                                |
| 3   | BFS60-1      | Cement mortar using 20% FA (by wt.%) as replacement of cement and 60% BFS and 40% MS (by wt.%) as replacement of sand | C:(BFS+FA) 1:(0.6+0.4) |
|     | BFS60-2      |                      |                                |
| 4   | BFS80-1      | Cement mortar using 20% FA (by wt.%) as replacement of cement and 80% BFS and 20% MS (by wt.%) as replacement of sand | C:(BFS+FA) 1:(0.8+0.2) |
|     | BFS80-2      |                      |                                |

3. Results and discussion
3.1 Thermal conductivity

In order to determine the thermal conductivity of samples, a thermal conductivity apparatus (of insulating slabs) was used.

The thermal conductivity of the tested samples was calculated after 10-minute intervals, when the thermal stability conditions were attained, and under fixed atmosphere conditions (results in table 2). Electric current was provided at frequency of 50 Hz, with phase difference (angle between current and voltage) as \( \pi/4 \). Voltage and current were provided to a heat source as 150V and 3.5A respectively. The average thermal conductivities \( k \) of the examined materials is reported in table 3. Based upon the results presented in table 2, one observes that the BF 80 mortar offers the best performances from the point of view of thermal insulation (minimum thermal conductivity). Such results are explained by the fact that the BFS80 mortar comprises a greater proportion of silicates/ alumina silicates, as compared to BFS40 and BFS60 mortars, which results in more controlled thermal conductivity.

### Table 2. Observations for thermal conductivity of the examined samples (T1: temperature of surface attached with heat source, T2: temperature of upper surface, dT: difference in temperature, dx: sample thickness in m).

| Samples  | T1 (°C) | T2 (°C) | dT | dx  | Thermal conductivity (W/mK) |
|----------|---------|---------|-----|-----|-----------------------------|
| REF-1    | 285     | 108     | -177| 0.0345| 1.07                        |
| REF-2    | 310     | 88      | -222| 0.0347| 0.95                        |
| BFS40-1  | 287     | 116     | -171| 0.0359| 0.85                        |
| BFS40-2  | 245     | 73      | -172| 0.036  | 0.84                        |
| BFS60-1  | 272     | 138     | -134| 0.0335| 0.69                        |
| BFS60-2  | 335     | 90      | -245| 0.0345| 0.70                        |
| BFS80-1  | 394     | 89      | -305| 0.0306| 0.66                        |
| BFS80-2  | 385     | 166     | -219| 0.031  | 0.65                        |

### Table 3. Observations of average thermal conductivity of two samples.

| Samples  | Average of thermal conductivity (W/mK) |
|----------|---------------------------------------|
| REF      | 1.01                                  |
| BFS40    | 0.85                                  |
| BFS60    | 0.70                                  |
| BFS80    | 0.65                                  |

3.2 Mechanical strength (Compressive strength)

The compressive strength of the mortar samples under examination was tested according to ASTM C39/C39M standard, by determining the peak load in kN for 4×4cm2 cross section specimens cut from the 11cm×11cm×3cm samples. A compressive testing machine with a capacity of 2000kN was employed, with an arrangement for automatic pacing. The experimental peak loads of the tested samples are shown in Table .

### Table 4. Observed average peak load and compressive strength.

| Samples  | Average peak load (kN) | Compressive strength (MPa) |
|----------|------------------------|----------------------------|
| REF      | 19.2                   | 12                         |
| BFS40    | 16.04                  | 10.025                     |
| BFS60    | 14.55                  | 9.09                       |
| BFS80    | 10.57                  | 6.6                        |
The results presented in table 4 show that the compressive strength of REF mortar was the greatest, followed by that of BFS40, BFS60 and BFS80 mortars. In order to further interpret these behaviors, surface porosity tests were performed.

3.3 Morphology and porosity (percentage)
A tool maker microscope (Make: Mitutoyo, Japan) was used to reveal the morphologies of composite at ×30, while metallurgical image analyzer (MIAS) software was used for the analysis of material porosity at ×100. Table 5 shows the average porosities measured for the examined materials.

**Table 5. Observations for average porosity (%).**

| Samples | Average porosity of samples (%) |
|---------|---------------------------------|
| REF     | 21.22                           |
| BFS40   | 18.51                           |
| BFS60   | 23.04                           |
| BFS80   | 29.65                           |

4. Conclusions
Following are the conclusions from this study:

1. The porosity of samples of BFS80 was observed as 29.65% greater than the REF samples (21.22%). Hence, these samples are better for construction sites where there will be more water logging problems.
2. As regards to compressive strength of samples is concerned REF samples has shown maximum (12MPa), followed by BFS60 (9.09MPa), BFS40 (10.025MPa) and minimum was observed for BFS80 (6.6MPa).
3. Based upon observations of thermal conductivity BFS 80 resulted into thermal conductivity of 0.65W/mK even better than the REF samples (1.01W/mK), making this sample best from thermal conductivity and heat capacity view point.

In future work, we will study the design and development of innovative sustainable composites, which mix the materials studied in the previous works with different green materials [19-23]. Additional future research lines will investigate the use of eco-sustainable materials for the design of next-generation meta-materials and structures, whose properties mainly derive from the geometry of the microstructure [24-30].

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