MECHANICAL PROPERTIES OF HIGH-STRENGTH MORTAR MADE WITH INDUCTION FURNACE STEEL SLAG AS FINE AGGREGATE

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ABSTRACT

Induction furnace steel slag as fine aggregate is a waste material produced during crushing the steel slag boulders to make coarse aggregate. Utilization of this waste as fine aggregate will reduce the demand for natural river sand (NRS) in the concrete construction works, and can play an important role in the sustainability of construction material in Bangladesh, as well as around the world. Within this context, this research work presents an experimental investigation on the physical and mechanical properties of high-strength mortar (HSM) made with three different replacement percentages (0%, 50% and 100%) of NRS by steel slag fine aggregate (SSFA). The cube specimens (50 mm x 50 mm x 50 mm) for compression and briquet specimens for tension tests are prepared at 7days, 14 days and 28 days. The failure mechanism of HSM under compression and tension is discussed as well. Furthermore, the dry density of mortar is also measured on the specimens that have been used for the compression test. The weight basis mix design with water to cement ratio of 0.3 and sand to cement ratio of 1.5 are used for all mortar mixes. The experimental results have shown that the compressive strength of mortar blocks made with SSFA is significantly higher as compared to mortar blocks made with 100% NRS. The average compressive strength of mortar tested at 28 days of 0%, 50% and 100% SSFA are, respectively, 49.6 MPa (7200 psi), 57.7 MPa (8370 psi) and 58.3 MPa (8450 psi). The compressive strength of mortar made with 100% SSFA at 7 days, 14 days and 28 days are on average 46%, 20% and 18%, respectively, higher than the mortar made with 100% NRS. The tensile strength of mortar is significantly higher for SSFA than NRS, which is 41% higher for mortar made with 100% SSFA than 100% NRS. This behavior could be attributed to higher surface texture, higher angularity and excellent surface roughness of SSFA than NRS. By contrast, the reduction in workability is observed for mortar containing SSFA than NRS due to higher angularity of SSFA and a bit higher temperature of fresh mortar at the time of placing. Moreover, it is shown that the density of mortar increases with the increased replacement percentage of NRS by SSFA, probably due to higher specific gravity (3.24 for SSFA and 2.56 for NRS) and better interlocking of cement paste with SSFA than NRS. Based on the results presented herein, it is demonstrated that SSFA can be used as a full replacement of NRS, which will not save money and energy, it will also solve the disposal problem, reduce the demand for natural fine aggregate.

Keywords: *Induction furnace steel slag, High-strength mortar, Compressive strength, Tensile strength, Density.*

1. INTRODUCTION

In South Asia, some countries like Bangladesh has very limited availability of natural aggregates due to geological features to build concrete structures and infrastructures. Therefore, the concrete industry mostly depends on burnt clay brick aggregate due to very limited availability of natural stones (Miah et al., 2019), which harms the environment (increases CO_2 in the air). Concrete is commonly used construction building materials in the globe, where fine aggregate has a significant role to provide strength and durability as well as the price of concrete. Typically, fine aggregate occupies about 20-30% of the total volume of concrete, and it is the second most important component of concrete after coarse aggregate since it helps to improve the various properties of concrete or mortar such as reducing the shrinkage, provide workability, volume stability, strength by filling the voids and durability to the concrete. Furthermore, fine aggregate is used to make brickwork, plastering, repairing work and retrofitting (e.g., ferrocement mortar).

In Bangladesh, natural river sand (NRS) as fine aggregate is mainly used which is limited, and the demand for sand is increasing due to the booming of the construction in Bangladesh. At the same time, the demand for other materials such as steel and iron are also increasing which increasing the waste materials as well. If this waste can be used in construction that will resolve the disposal problem, reduce the demand for new aggregates and reduce the cost and energy. This present study investigates the utilization of the induction steel slag as fine aggregate instead of NRS, which is the by-product of the steel manufacturing process. In the literature, it is shown that using this material has better mechanical properties, cost-effective and environment-friendly. The mechanical properties of concrete made with different replacement percentages (0%, 10%, 20%, 30%, 40%, 60%, 80% and 100%) of natural fine aggregate (NFA) by SSFA was investigated (Guo et al., 2019). The authors found that the compressive strength and toughness were higher for the concrete made with SSFA than the NFA. Another study showed that the incorporation of SSFA as a replacement of NFA improves the compressive strength and modulus of elasticity of concrete (Guo et al., 201). Though all the replacement percentage of NFA by SSFA has higher strength as compared to reference concrete, the optimum percentage of SSFA for the compressive strength of concrete is 20%. Moreover, the mechanical and microstructure of mortar made with four different replacement percentages (0%, 25%, 50%, 75% and 100%) of NFA by SSFA were investigated (Santamaría-Vicario et al., 2015). It was found that the compressive and flexural performance of mortar made with SSFA was increased with the replacement percentage of NFA. By contrast, a bit higher dry density of mortar made with SSFA was observed as compared to NFA. Similarly, it was observed that the incorporation of slag fine aggregate enhances the compressive, tensile and flexural strength of concrete (Devi and Gnanavel, 2014). Furthermore, it was found that the compressive and flexural strength of concrete increases with for all concrete mixes made with SSFA (Qasrawi et al., 2009).

Though a number of researchers found that the concrete made with SSFA has superior mechanical performances as compared to NFA, in Bangladesh, almost no investigation has been conducted yet on the physical and mechanical properties of high-strength mortar (HSM) made with induction furnace SSA as replacement of NRS. This HSM could be used in ferrocement technique and repairing work. Indeed, the mechanical properties of ferrocement mortar have a significant role to enhance the global performance of the retrofitted structure and the durability performance (corrosion) of ferrocement due to its lower net cover and higher surface area of the steel wire mesh. To do this end, comprehensive experimental studies are conducted on the possibility of using induction furnace steel slag as fine aggregate as a replacement of NRS. This research work aims to investigate the physical and mechanical (i.e., compressive and tensile strength) properties of HSM made with three different replacement percentages (0%, 50% and 100%) of NRS by SSFA.

2. EXPERIMENTAL INVESTIGATIONS

Two types of fine aggregates (Sylhet sand and SSFA) have been used in this study. Steel slag is a solid waste from the steel production industry. The steel slag chunks are collected from the local steel manufacturing company. During crushing the steel chunk to make coarse aggregate, fine dust is produced as well which has been used as fine aggregate in this study. The image of steel slag chunks and steel slag fine aggregate are presented in Figure 1. Both fine aggregates (natural river sand known as Sylhet sand: NRS, and steel slag fine aggregate: SSFA) are tested for grading, specific gravity and absorption capacity as per ASTM C136 and ASTM C128 standards, respectively. The specific gravity, absorption capacity and fineness modulus are 3.24, 1.0 and 3.04 for SSFA, respectively, and 2.56, 3.1 and 2.86 for NRS, accordingly. The sieve analysis of SSFA and NRS is presented in Figure 2. The weight basis mix design with water to cement ratio of 0.3, sand to cement ratio of 1.5 and air content of 2% are used for all mortar mixes. Since the water to cement ratio is lower, superplasticizer as a chemical admixture is used (0.5% by mass of total cement) to provide the workability of fresh mortar. To investigate the effect of SSFA on HSM, three different replacement percentages (0, 50% and 100%) of NRS by SSFA are used. The cube specimens (50 mm x 50 mm x 50 mm) are made to perform the uniaxial compression test of mortar as per the ASTM C109 standard. While the briquette specimens are used for the tensile strength test of mortar as per the ASTM C307 standard. The evaluation of compressive and tensile strength of mortar was investigated at 7, 14 and 28 days. The dry density of mortar was also measured on the specimens that have been used for the compression test.

Figure 1: Steel slag chunks (left) and steel slag fine aggregate (right), respectively.

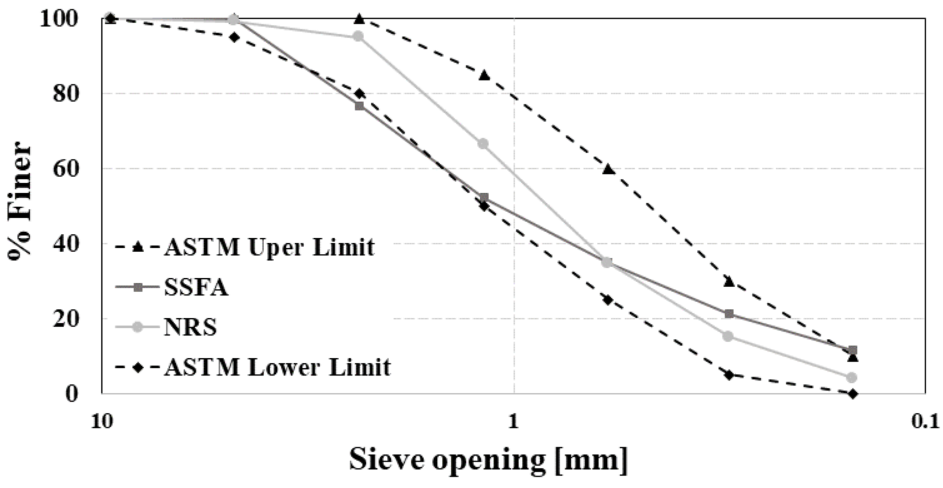


Figure 2: Grading curve of Sylhet sand (NRS) and SSFA, and comparison with the ASTM upper and lower limit.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Physical properties of fine aggregates

The specific gravity of SSFA is higher than the NRS (3.24 for SSFA and 2.56 for NRS), which could be responsible for the higher percentage of Fe_2O_3 of steel slag since it is the by-product of the steel manufacturing process, and that could provide a higher density of mortar. By contrast, significant lower absorption capacity (1% for SSFA and 3.1 for SSFA) is observed for SSFA than NRS, which implies that the mortar made with SSFA will absorb less water which is good for those structures which are exposed to water like the exterior wall, roof, repairing/strengthening structural elements, etc. This lower absorption capacity will delay the time of corrosion of steel reinforcement/steel wire mesh of ferrocement (the surface area of steel wire mesh is quite high) due to lower penetration and absorption of water. The closer visual observation showed that SSFA is highly angular in shape, sharp edges and has a higher rough surface texture than NRS, resulting in better interlocking in the mix that provides higher strength.

3.2 Fresh mortar properties

The mortar made with SSFA has lower workability than the NRS. The slump values of mortar made with 0%, 50% and 100% SSFA are 23 mm, 19 mm and 13 mm respectively. This behavior could be due to higher angular in shape, sharp edges and rough surface texture of SSFA than NRS, resulting in the reduction of the mobility of fresh mortar due to better interlocking in the mix. Similar results are found in the literature (Devi and Gnanavel, 2014; Qasrawi et al., 2009). This could be also linked to the concrete temperature at the time of placing. It is observed that the temperature of the fresh mortar at the time of placement is a bit higher for SSFA than NRS.

3.3 Mechanical properties

The compressive strength of mortar made with three different replacement percentages of NRS (Sylhet sand) by SSFA was conducted at 7, 14 and 28 days and presented in Figure 3. For every data set, three cubic mortar blocks are performed and then the average value is calculated. It is seen that the mortar made with SSFA has higher compressive strength at all curing ages as compared to 100% NRS. None of the specimens showed lower compressive strength as compared to the mortar blocks made with 100% NRS. The average compressive strength of mortar tested at 28 days of 0%, 50% and 100% SSFA are, respectively, 49.6 MPa, 57.7 MPa and 58.3 MPa. The higher compressive strength of concrete made with SSFA could be attributed to higher strength, coarser particle, higher angularity and rough surface of SSFA than NRS, which provide stronger interfacial transition zone (ITZ) between SSFA and cement paste. Indeed, ITZ is the weakest path for the failure of mortar or concrete during mechanical loading. These results are consistent with the results available in the literature (Guo et al., 2019; Santamaría-Vicario et al., 2015; Qasrawi et al., 2009).

To better understanding the role of different percentages of SSFA on the compressive strength of mortar, normalized compressive strength is calculated by dividing the strength of cube made with 100% sand (0% NRS) and compared with the results found in the literature, see Figure 4. The experimental results showed that as the percentage of SSFA increased, the compressive strength of mortar increased. At 7 days, a significant strength increment is observed for 100% SSFA as compared to other ages. The compressive strength of mortar made with 100% SSFA at 7, 14 and 28 days are on average 46%, 20% and 18% respectively higher than the mortar made with 100% NRS. The analysis of fractured surfaces of mortar specimens after compressive strength tests (see Figure 5a-c) showed that the failure plane passes through the SSFA and cement mortar. This failure pattern confirmed the stronger ITZ between the aggregate and cement paste.

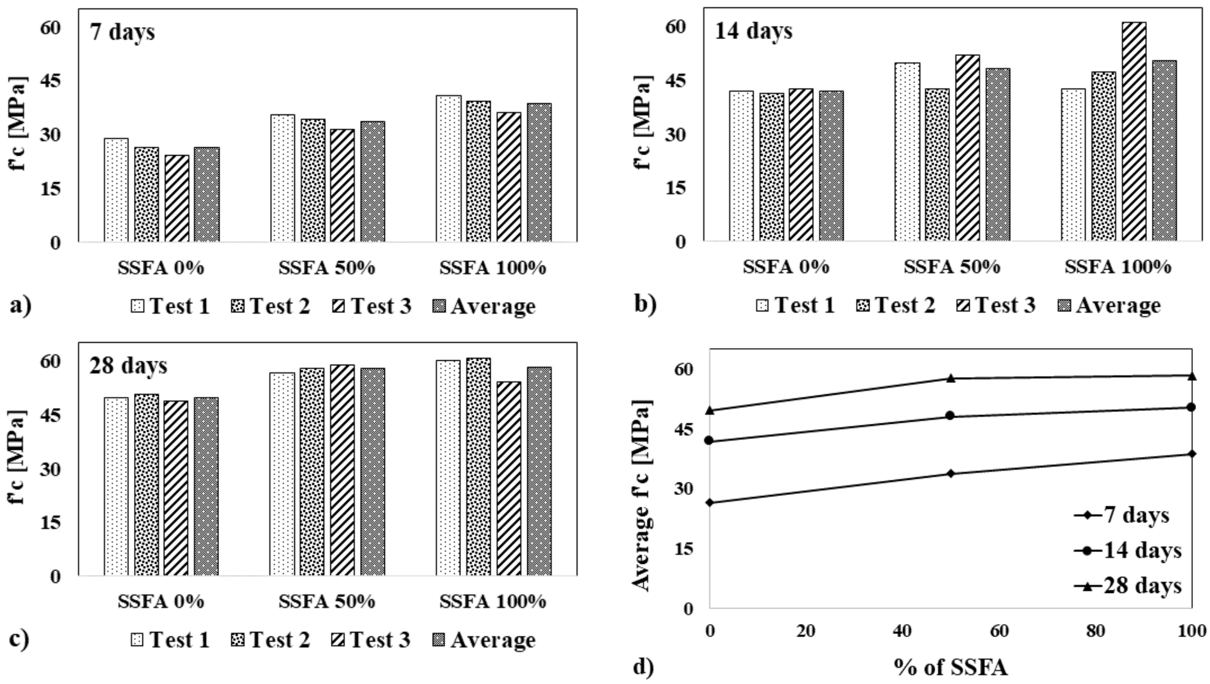


Figure 3: Compressive strength (f′c) of mortar conducted at 7, 14 and 28 days.

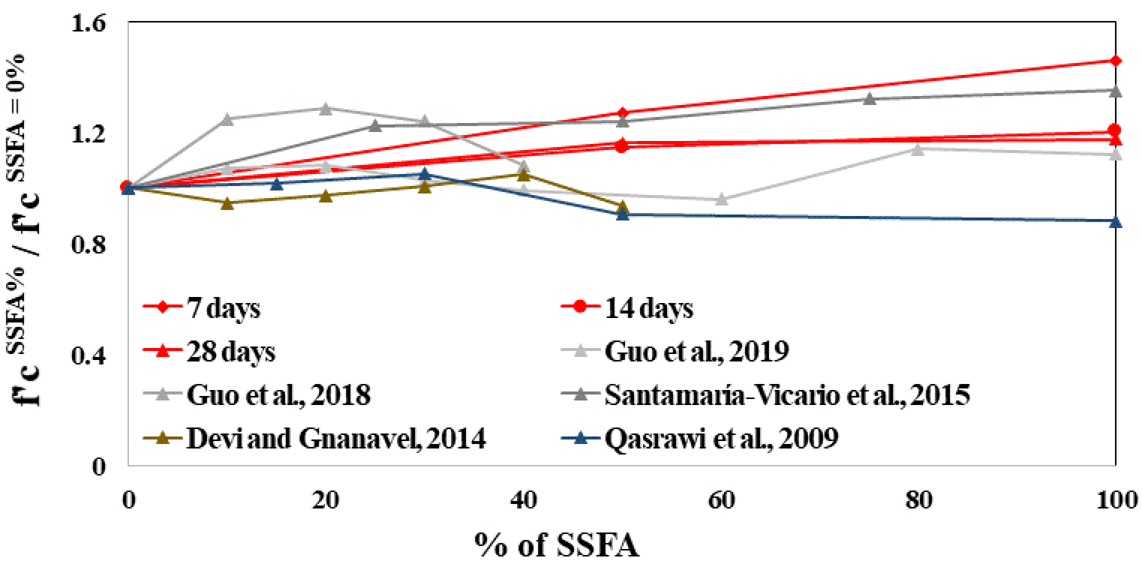
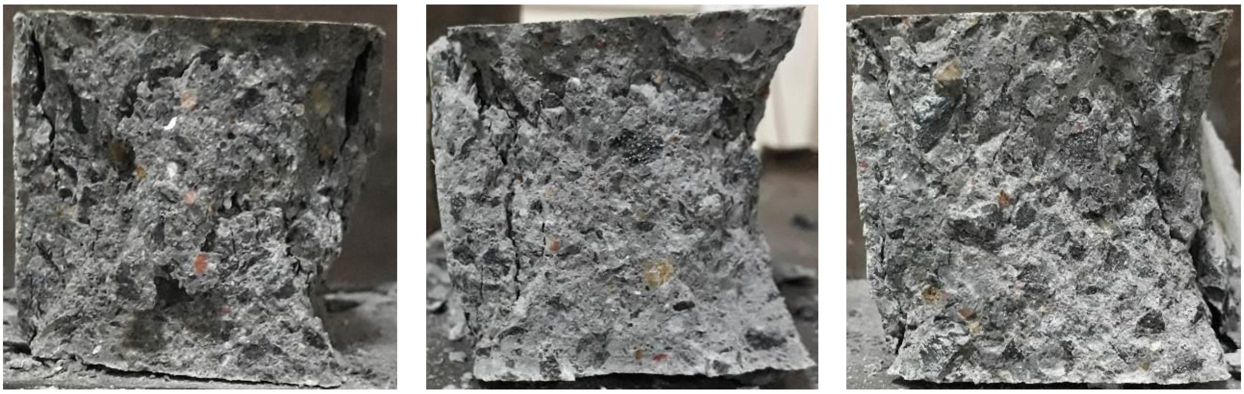


Figure 4: Normalized compressive strength of concrete mixes are compared with other results found in the literature.

It is observed that the experimental results are in good agreement with the results found in the literature. Most of the researchers found similarities with this experimental work. This high strength mortar made with SSFA provides a better future direction for the strengthening/repairing of the structures. In Bangladesh, ferrocement is commonly used for retrofitting due to available material and cost-effectiveness where the strength of the mortar plays an important role (Miah et al., 2019). Further, micro concrete or ultra-high performance concrete/mortar is needed to build highrise building, foundation and infrastructures where aggregates play a vital role in terms of strength and durability. Based on the results presented in this paper, this high strength mortar could be used in the ferrocement technique which will not provide higher strength, it will also provide better bonds among mortar, steel wear mesh and parent concrete.



a) 0% SSFA for f'c test b) 50% SSFA for f'c test c) 100% SSFA for f'c test

d) 0% SSFA for f't test e) 100% SSFA for f't test

Figure 5: Fracture pattern of the cubes for compression (a-c) and briquette for tension (d-e) tests, respectively.

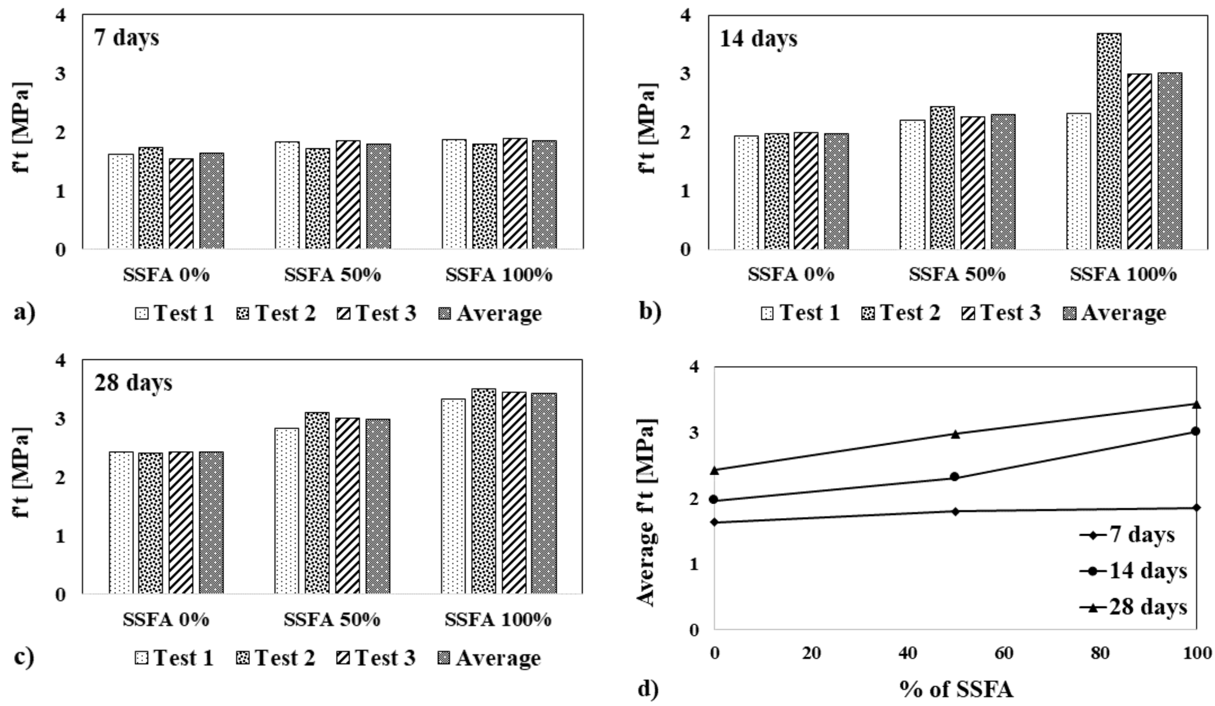


Figure 6: Tensile strength (f't) of mortar performed at 7, 14 and 28 days.

The tensile strength of mortar mixes made with different replacement percentages of NRS by SSFA is presented in Figure 6. It is seen that the tensile strength increases with the increasing percentage of

SSFA for all curing ages, which is in good agreement with the results of the compressive strength as discussed above. The tensile strength of mortar made with 0% SSFA, 50% SSFA and 100% SSFA are, respectively, 2.4 MPa, 3.0 MPa and 3.4 at 28 days, which increases the tensile strength up to 41% for the mortar when the NRS is fully replaced by SSFA. These results are consistent with the results available in the literature (Devi and Gnanavel, 2014; Qasrawi et al., 2009). As described briefly above, this higher tensile strength of mortar made with SSFA could be linked to higher strength, higher angularity and excellent surface roughness of SSFA than the NRS which ensured strong ITZ around the SSFA than the NRS. It is noted that the combined (cement mortar and aggregate) failure occurs for mortar made with SSFA (see Figure 5d-e). It is also seen that the mortar made with SSFA is more dense, less void, while some big voids are visible in mortar made with NRS, which allows lower mechanical load than SSFA mortar.

The dry density of mortar made with different replacement percentages of NRS by SSFA was measured at 7, 14 and 28 days and presented in Figure 7a-c. To better understand the effect of SSFA on dry density, Figure 7d is drawn with the average density as a function of % of SSFA. It is shown that the density of mortar is increased with the increasing replacement percentage of NRS by SSFA. The dry density of mortar made with 0% SSFA, 50% SSFA and 100% SSFA are, respectively, 2393 kg/m^3, 2572 kg/m^3 and 2809 kg/m^3 at 28 days. This higher density of mortar made with SSFA is directly linked with the higher specific gravity (3.24 for SSFA and 2.56 for NRS) and better interlocking of cement paste with SSFA than NRS. It should be noted that the compressive and tensile strength of mortar made with SSFA are significantly higher than NRS which increases the dry density of mortar. The higher density of concrete/mortar made with SSFA was also reported by other researchers in the literature (Santamaría-Vicario et al., 2015).

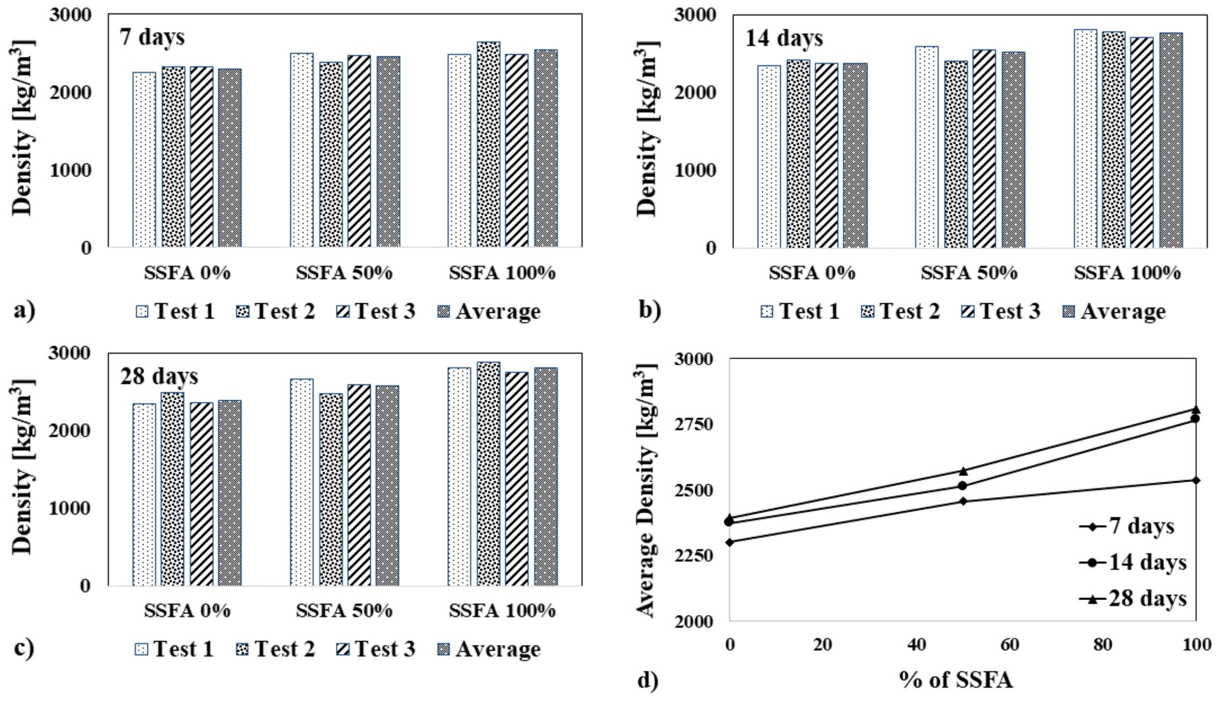


Figure 7: Dry density of mortar made with different replacement percentage of NRS by SSFA.

4. CONCLUSIONS

This paper investigates the physical and mechanical properties of mortar made with three different replacement percentage of NRS by SSFA. The cube specimens were made to perform compression tests and briquette specimens for the tensile test. The dry density of the mortar mixes was measured on the cube specimens which has been used for the compression test. Based on the results presented herein, the following conclusions can be drawn:

I. The compressive strength of mortar blocks made with SSFA is significantly higher as compared to mortar blocks made with 100% NRS. The compressive strength of mortar made with 100% SSFA at 7, 14 and 28 days are on average 46%, 20% and 18%, respectively, higher than the mortar made with 100% NRS.
II. The tensile strength of mortar is significantly higher for SSFA than NRS, which is about 41% higher for mortar made with 100% SSFA than 100% NRS.
III. Lower workability is noticed for the mortar made with SSFA than NRS, which could be attributed to the higher rough surface texture and better interlocking due to higher angularity of SSFA than NRS.
IV. The application of SSFA mortar could be more effective for the repairing work and the strengthening of the structures (e.g., ferrocement technique) since the strength of mortar is the key parameter that could enhance the global performance of the structures. Also, the mortar made with SSFA will prevent water penetration due to lower water absorption capacity of SSFA, which reduce corrosion and increase durability.

This study is limited to the evaluation of the compressive and tensile strength of the mortar. Other properties such as flexural strength and durability tests such as porosity, water absorption capacity and fire behavior of mortar need to be carried out. The outcome of this research project will encourage steel making industry to utilize the steel by-product in the concrete industry which are cost-effective and sustainable construction material since natural river sand is limited which is mostly extracted from the riverbed by dredging.

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