Effect of Powdered Nano-Local Banded Iron Formation (BIF) Rock on Some Mechanical Properties of Cementitious Concrete

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ABSTRACT

Banded Iron Formation (BIF) rocks are a significant source of iron ore, and they can also be used in the production of cementitious materials. However, the BIFs of the Egyptian Eastern Desert (ED) are not currently employed in steel iron manufacturing due to their elevated silica content and the technical challenges and high cost associated with extracting iron ore from them. Furthermore, the incorporation of nano-sized particles of BIF into cementitious mortar may impart specific characteristics that could enhance mechanical strength and durability, or even contribute to sustainability. This study examines the impact of nano- and powder-based materials derived from locally sourced BIF rocks on the properties of cementitious concrete when used as partial replacements for Ordinary Portland Cement (OPC). A comprehensive evaluation was conducted on concrete mixtures with varying cement replacement ratios, 1, 2, 3, and 4%, to assess the impact on key mechanical properties at different curing ages, 7, 28, and 90 days. The concrete samples exhibited significant enhancements in mechanical properties at all curing periods. The 2% Nano-BIF replacement yielded the most notable increase. Furthermore, X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) analysis demonstrated that the Interfacial Transition Zone (ITZ) between the cement paste and aggregates exhibited a robust compacted bond, indicating that local nano-BIFs have the potential to serve as an effective additive for enhancing the mechanical properties of cementitious concrete.

Keywords-nano-Banded Iron Formation (BIF); mineral admixture; cementitious materials; mechanical properties; XRD; TEM analysis

I. INTRODUCTION

The ongoing pursuit of novel construction materials that exhibit enhanced properties or reduced environmental impact has prompted researchers in the field of building materials to explore a range of innovative solutions. Among the plethora of potential avenues of inquiry, the application of nanotechnology to construction materials has emerged as a particularly promising avenue of research. The incorporation of nano-powdered materials derived from natural rocks into cementitious compounds has demonstrated considerable potential for offering a range of beneficial outcomes [1, 2]. It is widely acknowledged that the incorporation of nanoparticles enhances the mechanical properties of cementitious concrete. Nevertheless, there is a paucity of information regarding the impact of nanoparticle dosage, composition, and chemistry on the hydration reaction and properties of cementitious mortar [3]. Furthermore, the provenance and nature of these nanomaterials are of equal importance. One intriguing possibility is the usage of BIF powder, which possesses distinctive physico-mechanical properties and a unique chemical composition, as a nano-scale component in cementitious mortar and concrete. BIF is an ancient sedimentary rock, primarily consisting of alternating layers of iron oxides and other silicates, including jasper, chert [4-6]. The formation of these bands originated from Precambrian seas, occurring interlayered with units of Neoproterozoic volcano-sedimentary bands in numerous localities within the Egyptian ED, spanning an area of approximately 30,000 km² [7]. BIFs are defined by the presence of distinctive alternating layers. The initial layer, which ranges in thickness from a few millimeters to centimeters, is composed of either magnetite (Fe_3O_4) or hematite (Fe_2O_3) [8]. Subsequently, an iron-deficient silicate layer is present, constituting the subsequent stratum. These repeating layers exemplify the repeating pattern that is characteristic of BIFs, reflecting the cyclical processes that occurred during their formation. These rocks are distinguished by their alternating layers of magnetite and hematite, which are intercalated with quartz-rich layers. They may also contain accessory minerals, such as epidote, calcite, and chlorite [7, 9]. Despite concerns about using such an unusual material with a high iron content in cement, these rocks have captured the interest of geologists and building material scientists alike due to their potential applications. For example, in addition to its use as an important ore for iron extraction, BIF has potential applications in the development of cementitious products, composite stone, pavers, pigments, and plastic wood, as well as for gold exploration [6, 8, 9].

The objective of this research is to address a significant gap in the current understanding of mineral additives and cementitious materials. To date, no study has sought to evaluate the potential of the BIF rock as a component in cementitious mortar and concrete. In particular, the incorporation of the currently underutilized BIF rocks as a novel material into construction practices, in alignment with the overarching objectives of sustainability, and their incorporation within cementitious products, may prove beneficial for the environment. This is because these rocks are often discarded as waste materials in numerous Egyptian locations following iron or precious metal exploration [10]. Accordingly, the present study entails a comprehensive characterization of BIF, which will facilitate the formulation of optimal strategies for its integration with existing components, such as OPC. Secondly, the research will focus on determining the physico-mechanical properties, as well as the chemical and mineralogical composition of BIF, in accordance with the relevant international standards. Thirdly, the consequences of replacing a portion of OPC with nano-powdered BIF that can impact the material properties at a molecular level will be explored. From an engineering perspective, the incorporation of iron oxides may result in enhanced mechanical and durability characteristics, potentially leading to the development of safer and more durable structures. This is due to the improvement in critical parameters, such as compressive strength, durability, and resistance to environmental stresses [3, 11-13]. Furthermore, this partial replacement strategy has the potential to contribute to the development of more sustainable construction practices. For example, a reduction in the use of OPC, the production of which is associated with significant CO_2 emissions, could result in a lower carbon footprint for the construction industry. Researchers and engineers are engaged in ongoing efforts to enhance the performance and sustainability of these cementitious materials. Nano- and bulk iron oxide can be employed as a mineral admixture in concentrations up to 2.5% without adverse effects, resulting in improvements in certain mechanical properties [3, 14]. One emerging area of interest is the incorporation of nano powder-local BIF rock as an additive, which has the potential to significantly impact the properties of cementitious mortar and concrete. From an economic standpoint, the use of a relatively abundant material, like BIF, could result in cost-effective construction solutions.

In the local context, BIF is defined as precipitated marine sediments with an iron content exceeding 15% [7]. BIFs from the ED are not currently employed as a potential source of iron in steel manufacturing due to their elevated silica content [15]. Nevertheless, its potential use as a component in construction materials has been less extensively examined, in addition to the difficulties and costs associated with the extraction of iron ore from it, particularly if iron-bearing minerals are present in low concentrations and poor proportions. Furthermore, the incorporation of nano-sized particles of BIF into cementitious mortar may impart specific characteristics of the latter that could enhance mechanical strength, durability, and even contribute to sustainability. The Egyptian BIF studied in the current paper was obtained from a mining activity in the Fatira area, situated along the Qena-Safaga Road in the central Eastern Desert. BIF occurs as sharply defined stratigraphic units within a sequence of Neoproterozoic Island arc tholeiitic to andesitic/dacitic volcanic lava flows interlayered with pyroclastics. The lateral extent and thickness of individual iron ore bodies are typically on the order of tens of meters. The entire sequence (iron ore + host rocks) is characterized by a series of folds and thrusts, as shown in Figure 1, and underwent regional metamorphosis [16].

Fig. 1. Deformed layers of local BIF (left), rock masses of BIF with joints (right).

Mineralogically, BIF rock is distinguished by the presence of distinct iron-rich mineral bands, alternating with silica bands, as presented in Figure 2. The black micro-bands are primarily composed of dense magnetite, while the red micro-bands are predominantly chert and hematite, and the gray micro-bands suggest the presence of other mineral compositions. Magnetite is the dominant iron ore mineral, while quartz constitutes approximately 30% of most BIFs, occurring as an interstitial phase in addition to silicate-rich bands. These bands may consist of microcrystalline quartz (jaspilite) with inclusions of ultra-fine–grained iron oxide [7].

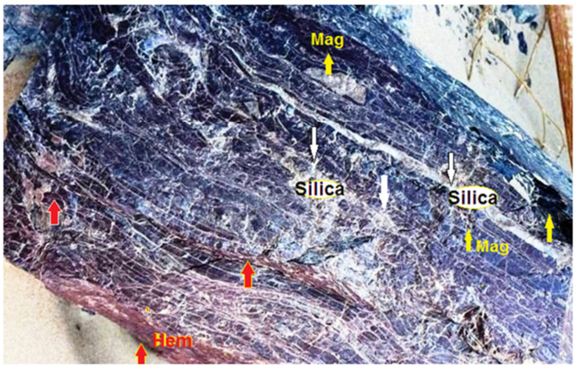

Fig. 2. Rock of local BIF showing alternating micro-bands of magnetite (mag), silica-rich, and hematite (hem) minerals.

II. METHODOLOGY

The objective of this methodology is to comprehensively assess the impact of nano-BIF powder as a partial replacement for OPC on various mechanical properties, including compressive strength, flexural strength, and splitting tensile strength at different curing ages, 7, 28, and 90 days. This assessment was conducted according to standardized testing procedures outlined in the Egyptian code [17].

A. *Material Characterization*

1) *Nano-BIF Preparation and Characterization*

The local BIF rocks were prepared at the National Central Metallurgical Research Institute, dried at 1000°C, and then crushed by a jaw crusher to 200 mesh prior to the manufacturing step. Nano-BIF was obtained through continuous grinding in a planetary ball mill, with a milling time of 28 hours. The resulting powder exhibits a reddish hue with a specific gravity of 3.3 and a surface area of 9900 cm²/g. Subsequently, a comprehensive characterization was conducted to gain insight into the physical and chemical properties of Nano-BIF. This includes techniques, such as XRD, which reveal that the powder is composed mainly of quartz and magnetite of moderate intensities, with traces of hematite and andradite minerals, as illustrated in Figure 3 (a). The agglomerated particles of nano-sized powdered BIF with the lowest particle sizes, reaching approximately 30 nm, are presented by TEM in Figures 3 (b) and (c). Additionally, the mean size of the powder is approximately 500 nm, as depicted in Figure 4, and the chemical composition of BIF was determined by X-ray Fluorescence (XRF) analysis, which revealed that it contains 42.7% silica and 30.2% total iron oxides, along with minor amounts of alumina, magnesia, calcium, and sodium oxides. The complete chemical composition is portrayed in Table I.

2) *Aggregates and Cement Characterization*

The aggregates, crushed dolomite and sand, and Portland cement, used in the current study, are subjected to rigorous testing to ascertain their conformity with the prescribed standards set forth in ASTM C33 [18].

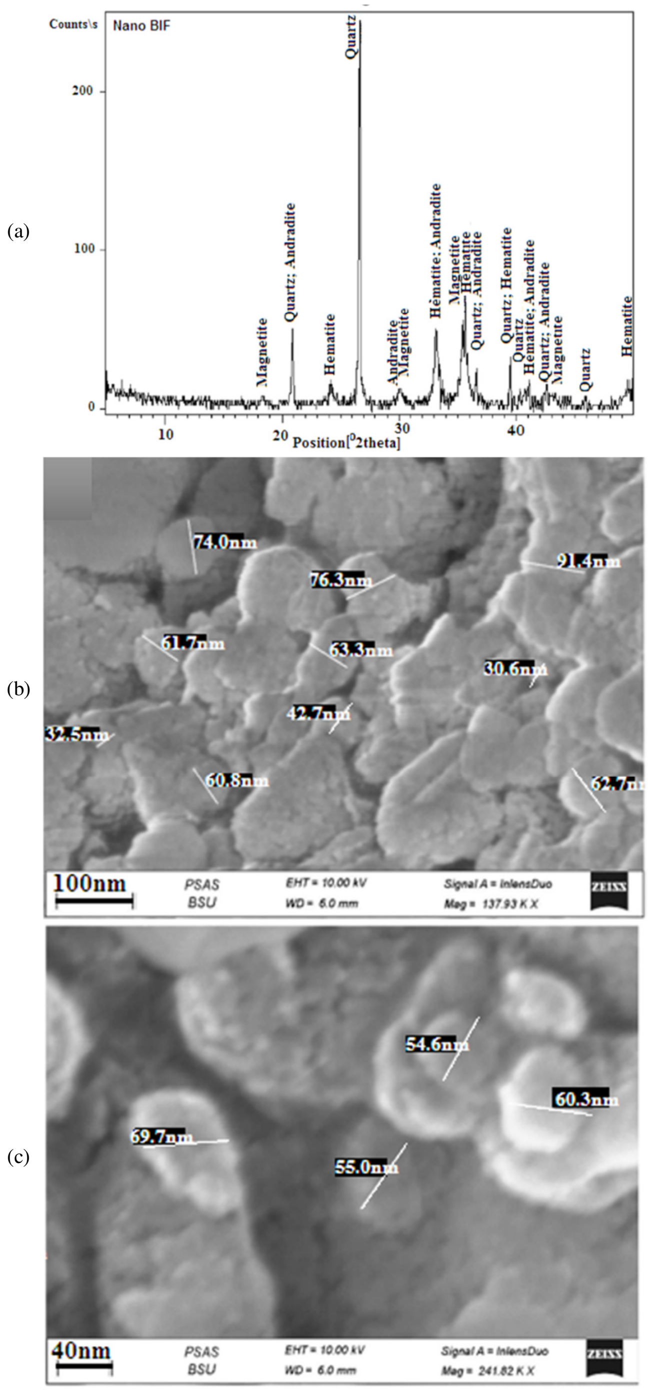

Fig. 3. (a) XRD pattern of the BIF powder, (b) ,and (c) electron microscope images illustrating agglomerated particles of nano-sized BIF powder.

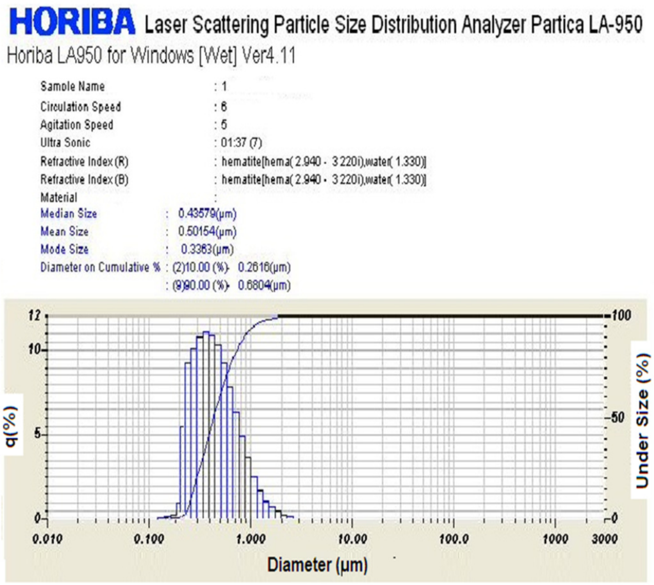

Fig. 4. Laser scattering particle size distribution of BIF powder.

The coarse aggregate is composed primarily of quartz mineral and is classified as siliceous gravel. The gravel was used with a specific gravity of 2.5 and an absorption rate of 1.9%, while its moisture content was maintained at 0%. The specific gravity of the sand was 2.5, its absorption was 1.21%, its humidity was 0.1%, its fine modulus was 2.4, and its bulk density was 1520 kg/m³. The grain size distribution of the fine and coarse aggregate, as per the ECP [17], is presented in Figure 5. The OPC used in this study, sourced from the Beni Suef Cement Company in Egypt and designated as CEMI 52.5 N, conforms to the specifications outlined in the Egyptian standard ES 4756 [19]. Its specific gravity was determined to be 3.15 g/cm³.

B. *Concrete Mix Proportions*

The proportions of the constituent materials for cementitious concrete samples are determined on the basis of the replacement ratios of Nano-BIF, expressed as a percentage, by 1%, 2%, 3%, and 4%, as detailed in Table II. Prior to mixing the ingredients, the Nano-BIF powder is separated by high-power ultrasound in order to ensure optimal distribution within the concrete mixture. The objective of the mix designs is to guarantee uniformity in the preparation of the samples. Concrete specimens are cast in the form of cubes 100 mm × 100 mm for the purpose of conducting compressive strength tests, and beams 500 mm × 100 mm × 100 mm for flexural strength tests. Cylindrical specimens 100 mm × 200 mm are employed for splitting tensile strength testing in accordance with the specifications set forth by the ECP [17]. All cast specimens are cured in a controlled environment, maintaining constant temperature and humidity conditions, in order to ensure uniform hydration and to facilitate mechanical strength evaluation at 7 days, 28 days, and 90 days.

TABLE I. CHEMICAL COMPOSITION ON THE STUDIED BIF POWDER AND CEMENT BY XRF ANALYSIS

Oxides	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**P_2O_5**	**SO_3**	**Cl**	**TiO_2**	**MnO**	**ZnO**	**LOI**	**Total**
BIF	42.70	10.40	30.20	5.71	1.75	1.21	1.09	0.79	0.24	0.61	0.96	0.22	0.04	4.14	99.97
Oxides	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	Cl	TiO_2	LOI	Total	Ins. R	Na_2O Eq.
CEM	19.70	4.41	3.34	63.24	1.24	3.07	0.17	0.20	0.13	0.09	0.34	4.06	99.99	0.51	0.31

III. RESULTS AND DISCUSSION

A. *Setting Time*

The initial and final setting times of cement, which are determined using the Vicat needle test, are employed as a quality control measure for cement characterization and are specified as a requirement in the ASTM C150 standard [20]. The findings indicate that the incorporation of modest quantities of the studied nano BIF powder into the raw mixture with cement may result in a notable increase in the initial setting time in comparison to the control cement sample without replacement, as shown in Figure 6. Furthermore, the final setting time demonstrates a gradual increase with the rise in replacement ratio. This suggests that a high concentration of BIF powder may impede the setting process, potentially influencing strength. These outcomes may be attributed to the agglomeration of heavy metals, such as Fe-oxides, which form dense coating layers around cement particles [21]. This barrier structure may be the primary factor responsible for the slowed reaction between water and the cement.

B. *Compressive Strength of Concrete*

The objective of this investigation is to ascertain the compressive strength of 100 mm × 100 mm cubes of concrete that incorporate nano-local BIF as a partial replacement for OPC. The analysis will commence with an examination of the results obtained at seven days of curing.

1) *Compressive Strength at 7 Days*

The highest compressive strength observed in the 7-day result was recorded for the 2% replacement ratio, with a value of 61.27 MPa. This represents a substantial increase of approximately 33.40% compared to the control sample, which exhibited a compressive strength of 46.03 MPa. The 1% and 3% replacement ratios also demonstrated enhanced compressive strength, albeit to a lesser extent. These findings underscore the beneficial impact of nano-BIF on the early compressive strength of concrete.

2) *Compressive Strength at 28 Days*

The 28-day curing period is a standard benchmark for evaluating the compressive strength of concrete, providing valuable insights into its mechanical performance over time. The results for concrete cubes continue to demonstrate the significant influence of nano-BIF as a partial replacement for OPC. These results corroborate the trend observed at seven days, with even more pronounced effects. The highest compressive strength at 28 days was observed in the 2% replacement ratio, with a value of 71.65 MPa. This represents a noteworthy increase of approximately 41.6% in comparison to the control sample, which exhibited a compressive strength of 50.61 MPa. Furthermore, the 1 and 3% replacement ratios demonstrated a notable enhancement in compressive strength. However, the 4% BIF replacement did not result in any gain in strength compared to the control sample. These findings highlight the sustained positive impact of nano-BIF on the compressive strength of concrete, particularly at higher replacement ratios.

(a)

(b)

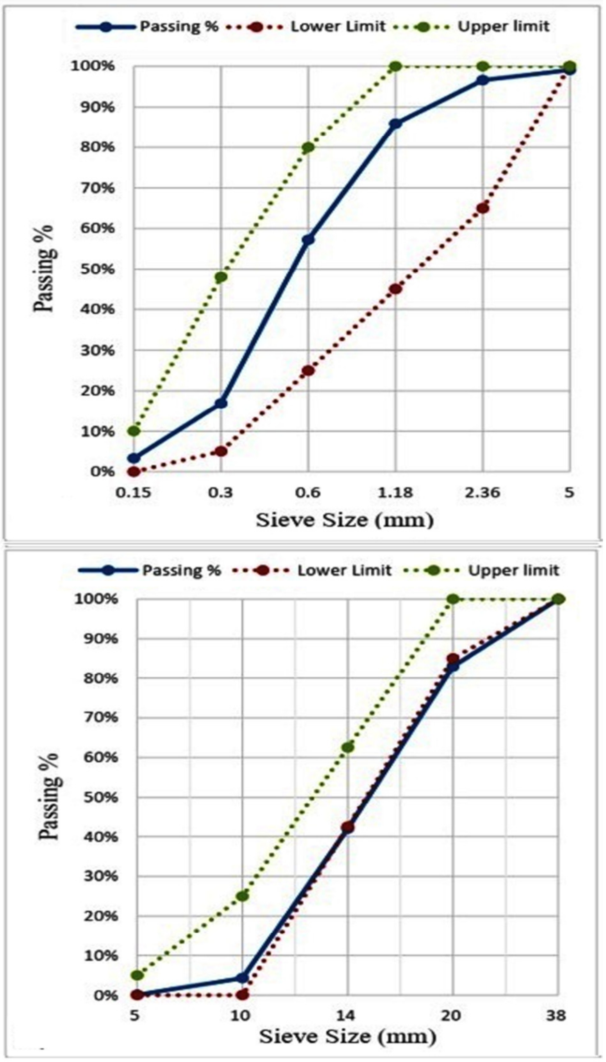

Fig. 5. Grain size distribution of (a) fine aggregates, (b) coarse aggregates.

3) *Compressive Strength at 90 Days*

The 90-day curing period represents a significant milestone for evaluating the long-term compressive strength of concrete. The results for 100 mm ×100 mm cubes continue to demonstrate the beneficial impact of nano-BIF as a partial cement replacement. Although the increase in strength is less pronounced than that observed at 28 days, it is nevertheless noteworthy. The 2% BIF replacement ratio continues to exhibit the highest compressive strength value observed at 90 days, with a value of 72.10 MPa, as shown in Figure 7. This represents an increase of approximately 20% compared to the control sample, which exhibited a compressive strength of 59.8 MPa. Furthermore, the 1% replacement ratio demonstrated a slight improvement in compressive strength. However, the compressive strength of the concrete samples containing BIF at doses of 3 and 4% was found to be significantly lower than that of the control sample at 90 days. This may be attributed to the effect of delaying the hydration process, which in turn affects the strength of the concrete with higher iron content (monotony-Hong). These results highlight the sustained positive effects of nano-BIF on compressive strength over an extended curing period, particularly at lower replacement levels up to 2%. The material appears to facilitate the gradual development of strength in concrete, thereby enhancing its long-term performance and durability.

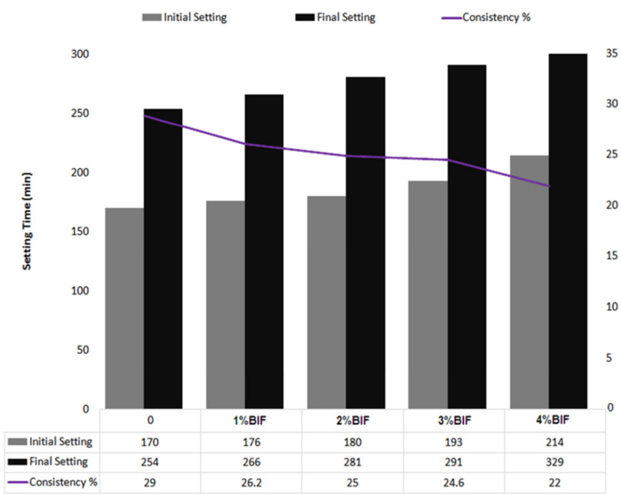

Fig. 6. Initial and final setting times for the studied cement pastes.

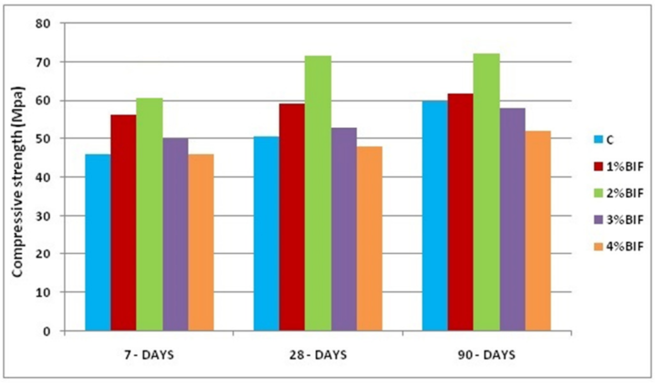

Fig. 7. Compressive strength of concrete: cubes 100 mm ×100 mm.

C. *Flexural Strength of Concrete*

The objective of the study was to investigate the flexural strength of concrete using beam specimens measuring 500 mm ×100 mm ×100 mm. The specific aim was to assess the impact of incorporating nano-local BIF as a partial replacement (1% and 2%) for OPC on flexural strength. The findings indicated that the incorporation of Nano-BIF resulted in notable enhancements in flexural strength, as depicted in Figure 8. The highest flexural strength was observed in the 2% replacement ratio, representing a substantial increase of approximately 15.6%, 19.3%, and 11.1% compared to the control sample at 7, 28, and 90 days, respectively. The flexural strength values at the specified ages were found to be 7.75 MPa, 11.53 MPa, and 12.04 MPa, respectively. The 1% replacement ratio demonstrated a notable enhancement in flexural strength. However, higher percentages, 3% and 4% BIF, exhibited a sudden decline in flexural strength, potentially due to the reduced cement hydration phases. These findings underscore the sustained positive impact of Nano-BIF particles, which effectively reinforce the concrete matrix with cement replacement up to 2%. This leads to a significant improvement in its ability to resist bending forces.

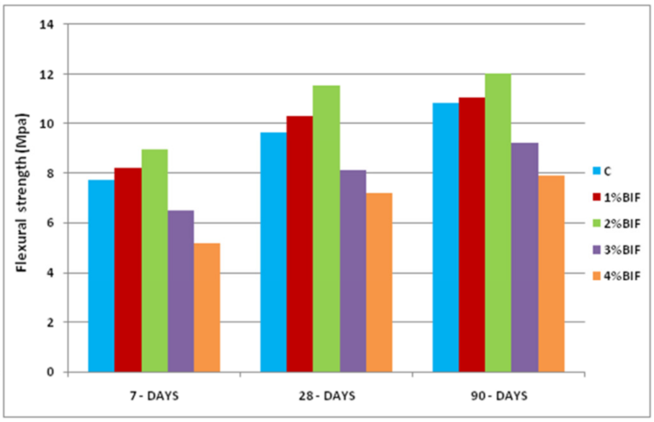

Fig. 8. Flexural strength of concrete: beams 500 mm × 100 mm × 100 mm.

D. Splitting Tensile Strength of Concrete

The splitting tensile strength results for concrete cylinders show the effect of nano-BIF as a partial replacement for Portland cement on the material's resistance to tensile forces, as presented in Figure 9. Additionally, as evidenced by the results of other mechanical tests conducted with up to 2% nano-BIF powder, there is a gradual increase in splitting tensile strength. The concrete mix containing 2% BIF demonstrates the highest value for splitting tensile strength. This represents a notable increase of approximately 19.8%, 16.2%, and 14% in comparison to the control sample at 7, 28, and 90 days, respectively (the specified ages' splitting tensile values are equal to 3.8 MPa, 4.08 MPa, and 4.11 MPa). In contrast to the outcomes observed for the 1% and 2% BIF replacement ratios, the higher replacement levels, 3% and 4%, also demonstrated a decline in splitting tensile strength, as evidenced by the findings of the other mechanical tests. The decline in strength observed with relatively higher replacement levels, 3% and 4%, can be attributed to the delayed mechanism previously observed in the setting time test, which subsequently affects the mechanical strength [22].

E. XRD Analysis

Figure 10 presents the XRD patterns of composite cement pastes for the optimum percentage of nano-BIF, as compared to the control paste. The predominant phases identified are quartz (SiO_2), portlandite (CH), calcium silicate hydrate (CSH), hematite (Fe_2O_3), and calcite ($CaCO_3$).

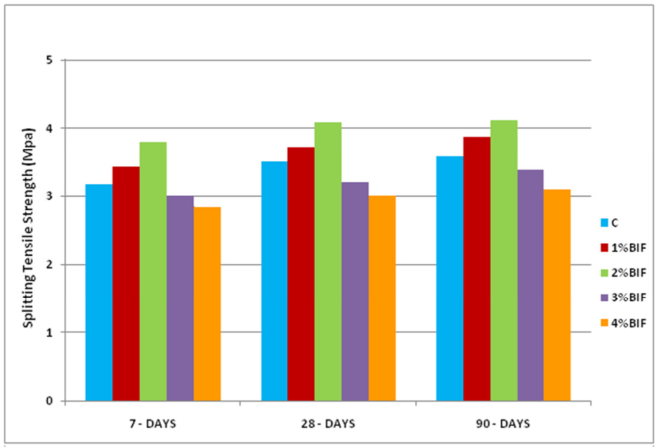

Fig. 9. Splitting tensile strength of concrete: cylinders 100 mm × 200 mm.

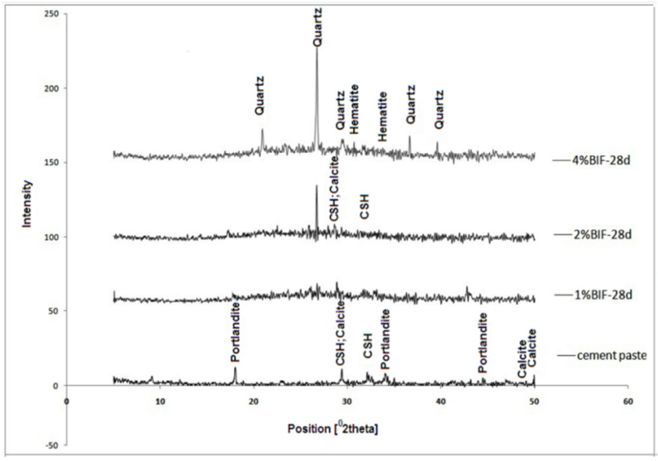

Fig. 10. XRD patterns of control and cement composites.

A comparison of the control paste with the BIF pastes reveals that, with the exception of the portlandite and CSH peaks, the intensities of the peaks are essentially indistinguishable. The portlandite peak of the 1% BIF and 2% BIF pastes exhibited a decrease, while the CSH peak demonstrated a slight increase in comparison to the control paste. The presence of hematite (ferric oxide) and the increase of the quartz mineral up to 4% BIF paste were primarily attributed to the substitution of BIF in the blended cement, with quartz and hematite being the main phases. Furthermore, the results indicated that when more than 2% of the studied BIF was replaced, it was considered a filler and no further pozzolanic activity occurred.

F. TEM Analysis

The TEM images of concrete samples incorporating the most effective 1% and 2% of nano-BIF used in this study are presented in Figure 11. The microstructure of the reference sample, after 28 days of curing, is observed to be homogeneous and dense. The ITZ demonstrates a robust bond between the cement paste and the aggregate. The TEM images of the concrete sample containing 1% Nano-BIF exhibit a distinctive texture compared to the TEM images of the reference samples, which display a denser and more compact hydration product structure and a favorable bond between the cement paste and the fine aggregates.

(a)

(b)

(c)

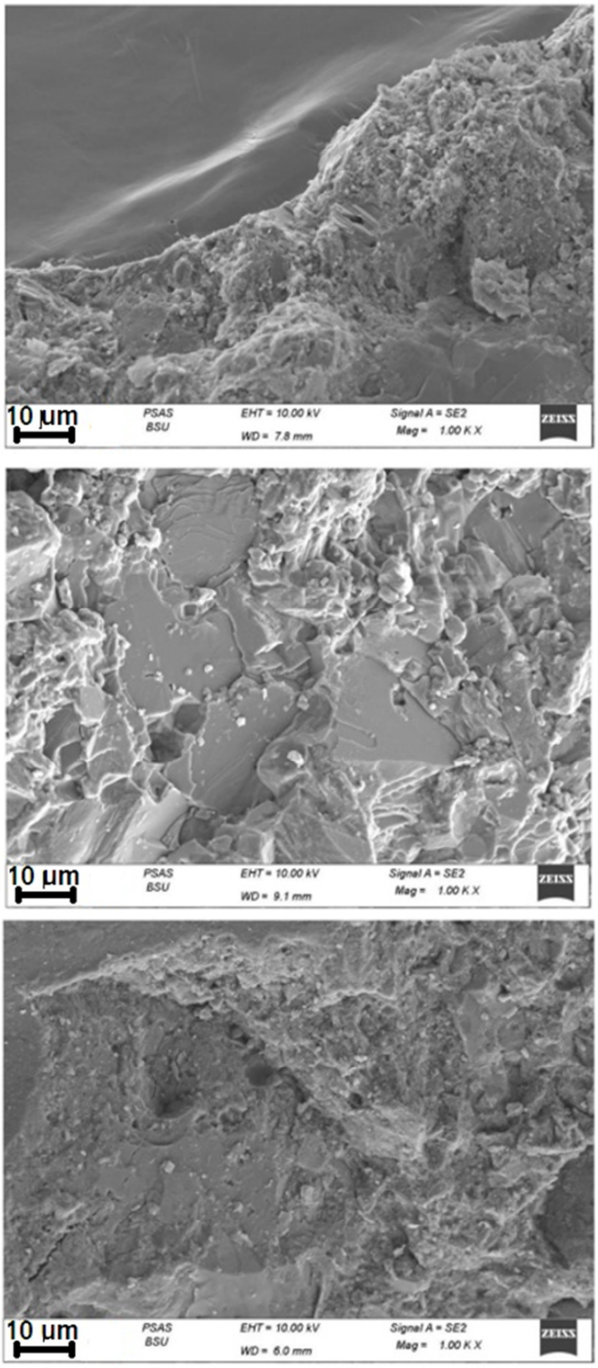

Fig. 11. TEM images illustrating ITZ between cement paste and aggregate at 28 days (a) control sample, (b) the cement paste of 1% nano-BIF, and (c) the cement paste of 2% nano-BIF.

Figure 11 (c) shows the microstructure of the concrete sample with 2% Nano-BIF replacement after 28 days. It can be observed that the interfacial transition zone between the cement paste and the aggregates is not readily discernible due to the highly packed nature of the cementitious matrix, which is influenced by the filling effect of BIF with a large specific surface area. This leads to a more compact paste structure and an increase in the extent of the bond. Additionally, the fracture surfaces of OPC paste observed under TEM demonstrate the presence of all hydrated cementitious products, including calcium silicate hydrate (CSH), as well as dispersed deposits of calcium hydroxide (CH) crystals within the hardened cement mortars, as portrayed in Figure 12. The addition of 1% Nano-BIF to concrete mixes has been observed to result in a lowering of the distribution of large crystals of CH throughout the microstructure. This indicates a reaction between CH and the free silica of BIF, resulting in the formation of excess CSH. The texture of the 2% nano-BIF sample is observed to be highly dense and more compact in comparison to the other samples. The observed improvement in the microstructure may be attributed to an enhanced bond formation between the nano-BIF particles and the free calcium hydroxide, as indicated by a gradual increase in the hydrated mineral phases, specifically CSH.

IV. DISCUSSION

The majority of cementitious materials used in contemporary concrete are formulated with cement and mineral admixtures, particularly those derived from quarry waste. Furthermore, the hydration activities of the blinded cement may vary depending on the quantity of mineral powder added. As the amount of mineral powder increases, the hydration and hydration reaction mechanism of the blinded cementitious material become more complex [23]. It has been demonstrated that the incorporation of a high proportion of BIF powder can delay the setting time of the concrete, which may subsequently influence the ultimate strength of the formed concrete. These findings align with the concept of iron-rich cements, which have been observed to exhibit prolonged setting times and slightly reduced mechanical strength [22]. Furthermore, powdered mineral bearing heavy metals have been observed to delay the setting time and retard the cement hydration process [21]. This phenomenon can be attributed to the coating effect of iron particles on calcium silicate particles, which create a barrier structure that impedes the reaction between water and the cement. In the event of a high ratio of iron oxides being added, there is a possibility that it may interfere with the C-S-H gel and prevent the setting process [24]. This suggests that BIF powder typically delays the hydration process and reduces the rate of hydration of cementitious materials. The greater the iron oxide content is, the more pronounced is the effect [23]. Additionally, a study attributed the observed hydration delay to the formation of brownmillerite ($Ca_4(Al_xFe_{(2-x)})_2O_{10}$), a solid solution with a slower hydration rate, which may occur if cement is incorporated with a higher content of iron oxides [25]. From a mechanical standpoint, incorporating small dosages of Nano-BIF up to 2% into the concrete mix has been proven to positively influence the studied concrete compressive strength in comparison to the control sample. However, there is still a paucity of information regarding the impact of varying replacement levels and the behavior of iron nanoparticles on the mechanical properties of concrete [3]. It is apparent that the 2% BIF demonstrates the highest compressive strength values at all curing times, namely 7, 28, and 90 days.

(a)
(b)
(c)

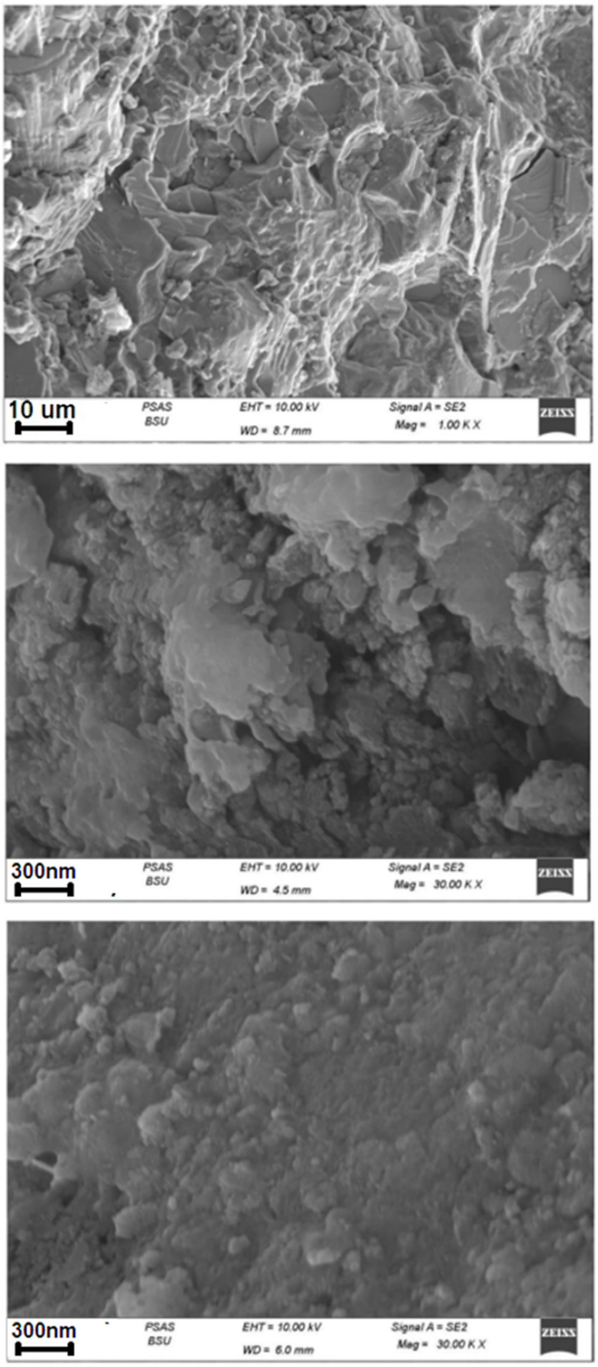

Fig. 12. TEM images illustrating CSH within the cement paste at 28 days (a) control sample, (b) the cement paste of 1% nano-BIF, and (c) the cement paste of 2% nano-BIF.

Authors in [3] revealed that a mixture comprising 2.5% of iron oxide nanoparticles demonstrated the highest compressive strength. However, an incremental increase from 2.5% to 3.0% resulted in a decline in strength, aligning with the findings of the aforementioned study. This may be attributed to the concentration of iron oxide in the cementitious admixture [13], or the specific type of iron oxide, which may influence the optimal percentage [14]. Furthermore, the accommodation of iron oxides in the interlayer of the CSH phases is considerably weaker [24]. The presence of Fe_2O_3 (hematite) has been shown to result in a notable decline in compressive strength [26, 27]. However, the gain in compressive strength observed at the early 7-day stage was 33.4%, and this was sustained over time, with a 41.6% and 20% increase recorded at the later curing stages of 28 and 90 days, respectively. The primary reason for this increase in mechanical strength is the filling effect of nano-BIF particles with a large specific surface area, which enhances and densifies the microstructure. An additional potential explanation is the pozzolanic effect, whereby the cement clinker initially reacts with water to form calcium silicate hydrate (CSH). Subsequently, when the alkalinity of the solution within the pore reaches a specific threshold, the mineral admixture initiates a pozzolanic reaction with portlandite ($Ca(OH)_2$), resulting in the formation of additional hydration products [23]. Furthermore, the optimal content of 2% with the studied nano-BIF is more effective than that reported by [3, 14]. This may be attributed to the distinctive composition of the local BIF, which differs from that of other sources or commercial iron oxides utilized in the aforementioned studies. As presented by XRF and XRD, BIF contains not only iron oxides, but also a greater proportion of silica in the crystalline or amorphous form. This provides an optimal source for enhancing the hydration products and improving the mechanical strength. The composition of iron ore has the potential to significantly impact the improvement of concrete properties. Additionally, the useful iron ore content percentage may be regulated by admixtures within the concrete [11].

The results of the flexural strength tests on concrete beams 500 mm × 100 mm × 100 mm demonstrated that the incorporation of nano-BIF resulted in a notable enhancement in flexural strength. The presence of a minimal percentage 0.01% of ferric oxide (hematite) has been observed to result in a slight decline in compressive strength. However, a notable increase in hardened cement flexural strength has also been documented [27]. The enhancement of flexural strength by 15.6% relative to the control is particularly notable at 7 days, indicating that nano-BIF contributes to rapid strength development in concrete. The increase in flexural strength persisted, reaching 19.3% and 11% at 28 and 90 days, respectively. Furthermore, the splitting tensile strength of concrete exhibited a comparable trend, with gains of approximately 19.8%, 16.2%, and 14% at 7, 28, and 90 days, respectively. It can be thus surmised that the incorporation of BIF into the cementitious mixture may serve to reinforce the interconnections between the constituent elements of concrete, thereby facilitating an overall enhancement in the mechanical attributes of the concrete. The influence of cement-based cementitious materials on the hydration reaction is a complex, multiphase, heterogeneous, and multistage process that varies at different reaction times. The impact of iron nanoparticle incorporation is primarily observed in the growth and transformation of calcium silicate hydrate crystals, which subsequently influences the mechanical properties of the mixture, resulting in enhanced compaction and adhesion. The concrete sample incorporating 2% nano-BIF exhibited a highly dense and compact texture, demonstrating superior packing and filler effects compared to other samples. This results in an improvement in the microstructure and an enhancement in the formation of bonds within the mixture.

V. CONCLUSIONS

The incorporation of Banded Iron Formation (BIF) rocks, which are currently regarded as useless local materials, into construction practices is aligned with the broader goals of sustainability. Furthermore, the use of these rocks as a powder addition in concrete mixes has the potential to offer environmental benefits, given that they are often discarded as waste materials in many locations following iron or precious metals exploration. The findings of this study elucidate the influence of local nano-BIF on the mechanical properties of cementitious concrete. The principal findings and their implications are:

- The optimal cement replacement ratio with local nano-BIF is 2%. This finding suggests that the use of nano materials with a 30% iron oxide content in concrete mixtures is limited to a maximum of 2%.
- The notable enhancement in compressive strength is 33.4%, 41.6%, and 20%, respectively, in comparison to the control sample at the ages of 7, 28, and 90 days, resulting from the substitution of cement with the optimal 2% nano-BIF.
- The replacement ratio of 1% nano-BIF exhibited minor improvements in compressive strength at all ages. While 3% replacement ratios displayed improved compressive strength at 7 and 28 days, they also demonstrated a notable decline in compressive strength relative to the control sample at 90 days. These finding merits further investigation in future research.
- The highest flexural strength observed for the 2% replacement ratio represents a substantial increase of approximately 15.6%, 19.3%, and 11.1% compared to the control sample at the ages of 7, 28, and 90 days, respectively. Additionally, the highest splitting tensile strength value demonstrates a notable increase of approximately 19.8%, 16.2%, and 14%, respectively, in comparison to the control sample at the ages of 7, 28, and 90 days.
- The 1% replacement ratio also demonstrated enhanced flexural strength and splitting tensile strength, in contrast to the higher 3 and 4% replacement ratios, which exhibited a decline in mechanical strength. It is therefore recommended that the BIF be used in a way that is not beneficial and that the amount of waste deposited in landfills be reduced. Further studies should be conducted to investigate the potential of incorporating additional supplementary minerals to address the deficiencies associated with BIF.
- The Transmission Electron Microscopy (TEM) analysis revealed that the Interfacial Transition Zone (ITZ) between aggregates and cement paste contains 2% nano-BIF, which is not readily discernible due to the enhanced bond strength. The texture of the 2% nano-BIF sample was observed to be highly dense and more compact in comparison to the other replacements. The specific mineralogical composition of BIF, which contains a relatively considerable amount of silica in addition to iron oxides, plays an important role in improving cement hydration to a greater extent than other iron-bearing materials observed in previous studies.
- The collective findings highlight the potential of nano-BIF, with its distinctive mineralogical composition, as an effective additive for enhancing the mechanical properties of cementitious mortar and concrete. The nano-scale particles within nano-BIF appear to enhance the density, cohesion, and resistance to compressive and tensile forces of the material to which they are added.
- The local nano-BIF has demonstrated a potential for achieving rapid strength development, sustained strength over time, and, to some extent, improved resistance to tensile forces.

Nevertheless, further research is recommended to explore the long-term performance of nano-BIF under various environmental conditions and its compatibility with different concrete mixes. Furthermore, additional research is required to ascertain the economic viability of its production and application.

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