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Original Article

Experimental Investigations of Binary Blended Concrete Containing Incinerated Biomedical Waste Ash

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Abstract - *Medical waste from various sources, including clinics, hospitals, and research institutes, poses a significant risk to human, plant, or animal life today or in the future and is referred to as Biomedical Waste (BMW). Due to its abundance, it cannot be processed or disposed of without special protections. BMW is normally disposed of in landfills after being burned in incineration facilities, producing Incinerated Biomedical Waste Ash (IBMWA). None of the landfills, however, are leak-proof. This study describes how using IBMWA as a cement substitute affects the strength and durability of concrete. A control concrete mix and five concrete mixtures with different amounts of IBMWA (2.5, 5.0, 7.5, 10 and 12.5%) were made for this comparison. Along with the microstructure, the values of water absorption, density, drying shrinkage, slump, compressive, flexural, and split tensile strength up to 90 days were examined. The strength metrics indicated optimum values at 7.5% replacement levels despite a considerable fall in slump values with increasing IBMWA%. With rising IBMWA replacement values, there was an increase in water absorption, density, drying shrinkage, and UPV. On all days, drying shrinkage and IBMWA% exhibited a linear connection. The presence of Wollensite mineral plays a pivotal role in the structural performance of the resulting concrete, forming denser microstructure.*

Keywords - *Concrete, IBMWA, Mechanical properties, Durability, Half-cell potential, Hazardous waste.*

1. Introduction

For medical centres and waste management authorities, the rising number of BMWs in India, especially during the COVID-19 pandemic, has presented considerable challenges. To ensure safe and efficient BMW management, the Central Pollution Control Board (CPCB) [1] has set new regulations for the handling and disposing surgical face masks, gloves, and leftover patient food. The pandemic has caused a significant increase in the average daily production rate of BMWs from 500 to 750 g per bed before the epidemic to 2500-4000 g per bed [1], emphasising the necessity for sufficient resources and infrastructure to treat these wastes [1].

To prevent adverse environmental or public health effects, BMW management procedures, such as amount estimation, type identification, preliminary treatment, distribution, processing, and final disposal, must be methodically carried out [2-6]. This calls for qualified employees, suitable facilities and equipment, and adherence to legal requirements [7, 8]. It should be mentioned that effective management of BMWs is essential to safeguard environmental safety and public health in general [9]. The right technology could significantly reduce the pressure on BMW management [10, 11]. BMW segregation at entrance points is a crucial step in their management since it helps with better detection and management [12]. Modernising current treatment and disposal procedures and creating new technologies can help handle the increasing number of BMWs [13-16]. Adopting new laws and regulations may also help address the problems caused by BMWs [16]. Overall, efficient supervision of BMWs is crucial to maintaining the safety and health of the public, and medical facilities must take the necessary action to address this issue.

Although treatment centres have been set up having a capacity of 800 tonnes per day [12], Figure 1 depicts the rising trend in BMW generation in India, and the failure to achieve 100% treatment points to the need for changes in policy execution and treatment facility management. Efficient BMW management strategies are essential given the ever-rising BMW generation over time. There are various methods for handling BMW.

These include the autoclave or steam treatment technique [17], the microwave treatment [18], the chemical treatment [19, 20], the incineration [21], the dry heat treatment [22], the pyrolysis [23, 24], the encapsulation and inertization [25], and the sanitary landfill [26]. The treatment technique should be chosen according to the waste characterisation and assessment, local laws and regulations, and other factors [27].

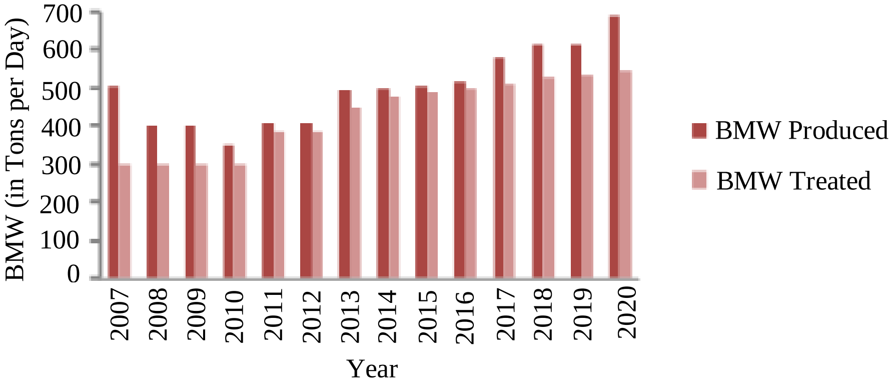

Fig. 1 BMW produced and BMW treated in India from 2007-2020 data collected from the CPCB [3]

Burning shouldn't be the primary choice for BMW treatment because it could harm the environment. Like incineration, several processes don't produce hazardous trash, and processed waste can be used to improve soil. Therefore, when choosing a BMW treatment technique, it is crucial to consider the environment's impact and the possibilities for reusing treated trash. To avoid contaminating the environment, Incinerated BMW Ash (IBMWA) must be disposed of correctly [28, 29]. The ash must be identified and handled accordingly if dangerous compounds are present. Metals and ions can be less likely to seep into the environment when the raw ash is modified.

Solidification/stabilisation, vitrification, and chemical fixing are techniques for handling incinerator ash [26, 28]. These techniques can lessen the leaching risk and immobilise the ash's dangerous materials. After being processed, the ash can be disposed of safely in a landfill or used to make concrete or bricks for buildings [29, 30]. It is crucial to adhere to the rules and regulations for hazardous waste disposal to reduce its influence on the environment.

Burning ash has created lightweight aggregates, pottery, bricks, concrete, and roads [28]. While Filipponi et al. [32] reported that IBMWA to total solid substitutes were altered across the range 10-80% (10, 20, 30, 50, and 80 percent); Anastasiadou [31] studied four alternative ratios of cement with fly ash and cement with bottom ash mixes (60:40, 50:50, 40:60, and 30:70 w/w).

At varied curing times, the solidified matrix's compressive strength was assessed. The results after 28 days reveal that when more than 50% IBMWA is applied, the matrix exhibits a slight pozzolanic tendency. The use of IBMWA as Supplementary Cementitious Materials (SCM.) in concrete was suggested by Aubert et al. [33] after examining the effect of IBMWA on the resilience and compressive strength of cured concrete. The elements influencing the strength gain process in concrete integrating IBMWA were recently outlined by Katare et al. [34].

2. Research Problem

From the literature review above, it is clear that there is plenty of room for using IBMW as SCM. in a concrete mix because it also functions as a pozzolanic material due to its high concentration of calcium oxide, which accounts for a high percentage of CaO, SiO_2, and Al_2O_3 (40.21%, 20.1%, and 11.13%, respectively, of the primary component of healthcare waste ash) [29, 34].

According to some findings from rheological research and mechanical strength characteristics, IBMWA may be able to replace cement up to 10% of the time. To determine the viability of IBMW as a partial replacement for cement, however, more research, notably on durability issues, must be done. Consequently, the following goals of the current work:

- To experimentally investigate the performance of concrete incorporating IBMWA as a partial cement substitute at replacement levels of 0%, 2.5%, 5%, 7.5%, 10% and 12.5%.
- To study the fresh, hardened and selected durability properties of concrete at different ages of curing, namely, 7 days, 28 days, 56 days and 90 days.
- To understand the microstructure of the resulting concrete and thus explain the phenomenon of strength gain/loss and the mechanism of different durability properties.

3. Materials and Methods

3.1. Materials

The current study employed the OPC. 53 grade verifying IS 12269-2013 [35]. Table 1 lists the cement's physical characteristics, whereas Table 2 lists its chemical characteristics. After complete cleaning in water and air-drying for 24 hours, coarse aggregates, 20 mm down, according to I.S.: 2386-1963 (Revision 2016) [36] with the parameters specified in Table 3 were used. This study employed river sand that complies with I.S.: 383-2016 [37] and is in Zone III. The physical characteristics of fine aggregates are shown in Table 4. Figure 2 depicts the particle size distribution of river sand.

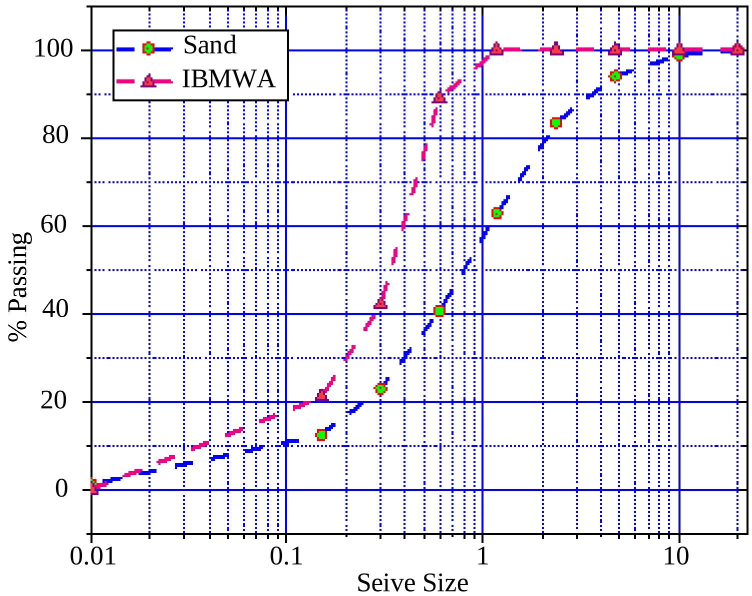

Fig. 2 Particle size distribution of sand and IBMWA

Table 1. Physical properties of O.P.C. (53 grade) confirming IS 12269-2013 [35]

Fineness (%)	**Le Chatelier Soundness (mm)**	**Specific Gravity**	**Consistency (mins.)**	**Setting Time (mins.)**		**Compressive Strength (MPa)**		
				IST	**FST**	**3 Days**	**7 Days**	**28 Days**
2.05	7	3.15	29	101	252	29	42	60

Table 2. Chemical properties of O.P.C. (53 grade) in % confirming IS 12269-2013 [35]

Loss on Ignition	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**K_2O**	**Na_2O**
3	65.53	16.91	4.47	4.88	0.81	0.35	0.16

Table 3. Physical properties of coarse aggregate confirming to I.S.: 2386-1963 (Revision 2016) [36]

S. No.	**Property**	**Units**	**Values**
1	Aggregate crushing value	%	20.62
2	Aggregate impact value	%	10.48
3	Los Angeles abrasion value	%	12.08
4	Bulk density	kg/m^3	1623
5	Fineness modulus	%	6.3
6	Water absorption	%	0.45
7	Flakiness index	%	6.9
8	Elongation index	%	11.5
9	Specific gravity	-	2.66

Table 4. Physical properties of river sand confirming to I.S.: 383-2016 [37]

S. No.	**Property**	**Units**	**Values**
1	Bulk density	kg/m^3	1532
2	Fineness modulus	%	2.48
3	Water absorption	%	0.57
4	Specific gravity	-	2.62

A commercial company, M/s J.K. Medical Waste Management System, Chanderi, India, provided the IBMWA, which was burned at 1200°C. Using a powder approach, the global makeup of the several chemicals found in IBMWA was ascertained using a Bruker D8 advance X-Ray Diffractometer (XRD). At 45 kV and 40 mA, the X-ray's wavelength was 0.154 nm Cu K radiation.

With a step size of 0.02o, the XRD spectrum was obtained from 0o to 80o of a two-angle. Figure 3 presents the XRD pattern. The present chemicals were analysed using the Rietveld Analysis software X'pert HighScore Plus. For phase identification, Pearson's Crystal Structure Database was employed. Albite, Wollastonite, SiO_2, Al_2O_3, and Fe_2O_3 are the principal substances discovered in IBMWA. Wollastonite is a complex substance with a cement-like particle size that contains Calcium Oxide, Silicon Dioxide, and minute amounts of various metals, including Aluminium, Magnesium, and Manganese.

According to investigations [38, 39], the use of Wollastonite increases early age strength and decreases shrinkage [40], reduces water absorption [41], and increases resistance to chloride migration, carbonation, and corrosion [42]. The inclusion of Wollastonite in IBMWA was, therefore, expected to alter the final concrete's characteristics significantly. Nearly 89% of IBMWA's particles made it through a 600-micron sieve, and the fineness modulus was 3.11 (Figure 2).

Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive Spectroscopy (EDS) was employed to analyse the morphology of IBMWA. The compounds were analysed using a Hitachi S-3400N SEM with EDS. with a 2 mm probe diameter, a 15 kV accelerating voltage, and a 50 nA probe current, with an estimated inaccuracy of 2 %.

Figure 4 displays the Back Scatter Electron Image (BSEI) of IBMWA placed on epoxy. High Ca, Si, Al, and Fe content was found in EDS spot analysis, correlating with the XRD results and creating Albite, Wollastonite, Al_2O_3, and Fe_2O_3. Furthermore, a sizable number of pores can be found in the microstructure, showing that IBMWA is porous. As a result, introducing such a substance is anticipated to significantly alter the concrete's physical, mechanical, and durability qualities.

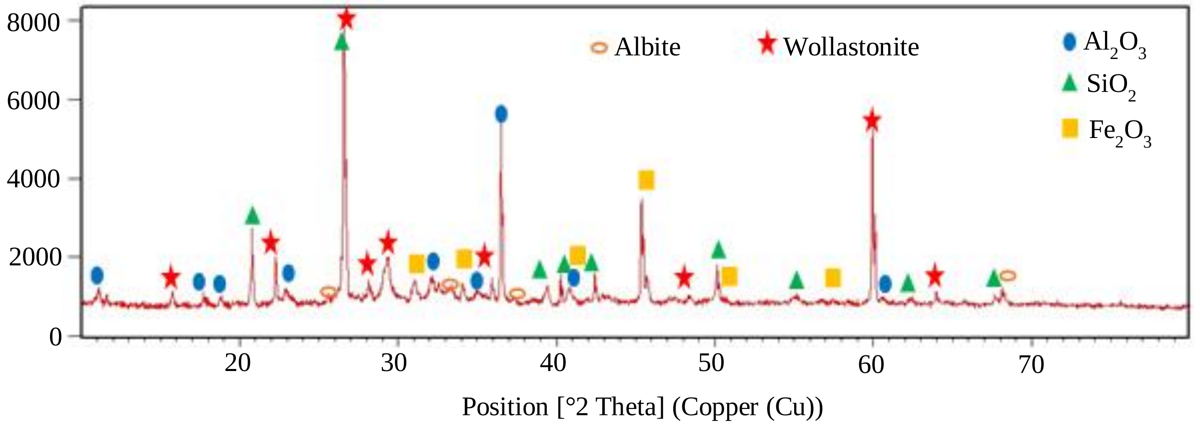

Fig. 3 XRD of IBMWA

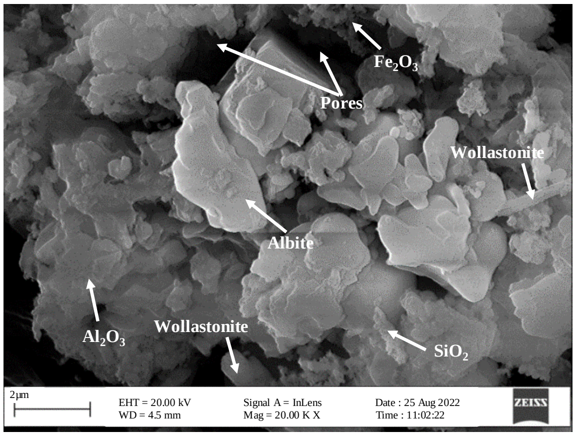

Fig. 4 SEM-EDS of IBMWA

3.2. Methods

3.2.1. Concrete Casting and Curing

The mixes were produced by partially replacing cement with IBMWA in different percentages ranging from 0 to 2.5, 5.0, 7.5, 10.0 and 12.5 percent. The mix design was per IS 10262-2019 [43]. The corresponding mix nomenclature and proportions are shown in Table 5. Details about the testing methods are presented in Table 6.

Table 5. Mix proportion and nomenclature of IBMWA incorporated concrete

Concrete Mix Nomenclature	Cement Replacement (%)	Mix Proportions in kg/m^3				
		Cement	**Fine Aggregate**	**Coarse Aggregate**	**IBMWA**	**Water**
IBMWA0	0	384	694.57	1140.67	0	192
IBMWA2.5	2.5	374.3	695.57	1140.67	9.625	192
IBMWA5	5	364.5	695.57	1140.67	19.25	192
IBMWA7.5	7.5	355.8	695.57	1140.67	28.875	192
IBMWA10	10	345.6	695.57	1140.67	38.5	192
IBMWA12.5	12.5	335.8	695.57	1140.67	48.125	192

Table 6. Details of experiments carried out

S. No	Test	Age of Concrete (Days)	Specimen Size (mm)	Apparatus/Instrument	Reference
1	Slump	Fresh concrete	-	Standard Slump Cone	[44]
2	Water Absorption	28, 56, 90	150x150x150		[45]
3	Density	28	150x150x150		[45]
4	Compressive Strength	7, 28, 56, 90	150x150x150 (cube)	Compression Testing Machine / Universal Testing Machine	[46]
5	Splitting tensile Strength	7, 28, 56, 90	100 Diameter and 200 Height (cylinder)	Compression Testing Machine / Universal Testing Machine	[46]
6	Flexural Strength	7, 28, 56, 90	100x100x500 (prism)	Flexure Testing Machine	[46]
7	UPV	28	150x150x150	PUNDIT	[47]
8	Drying Shrinkage	28,56,90, 112, 365	100x100x300 (prism)		[47]
9	Scanning Electron Microscopy	28	Samples of SEM	SEM Scanning Electron Microscope (Hitachi S-3400N)	-

4. Results and Discussion

4.1. Slump Test

Figure 5 displays the findings of slump values in mm for different combinations. As shown in the figure, all the mixes show a declining trend in slump value compared to the control mix. An equal quantity of water (192 kg/m^3) was added to all the concrete mixes to maintain identical conditions.

Water was absorbed due to the inclusion of IBMWA, which is naturally highly porous, as demonstrated by SEM images (Figure 4). The need for water grew as a result. As a result, less water was available to lubricate the aggregate surface. The rough shape of IBMWA particles made the friction much worse.

As a result, a cohesive, sticky, and rigid matrix was produced. Due to the porous IBMWA's larger surface area, the slump also decreased. As a result, during mixing, IBMWA particles absorbed more water than fine aggregates.

Kaur et al. [29] reported similar outcomes as well. Compared to IBMWA10, IBMWA12.5 exhibits a dramatic reduction in slump (almost 30%). As a result, it is impossible to prepare concrete using a continuous amount of water above a replacement level of 12.5%.

This shows that absent admixtures, more significant replacement levels may not be feasible when integrating IBMWA.

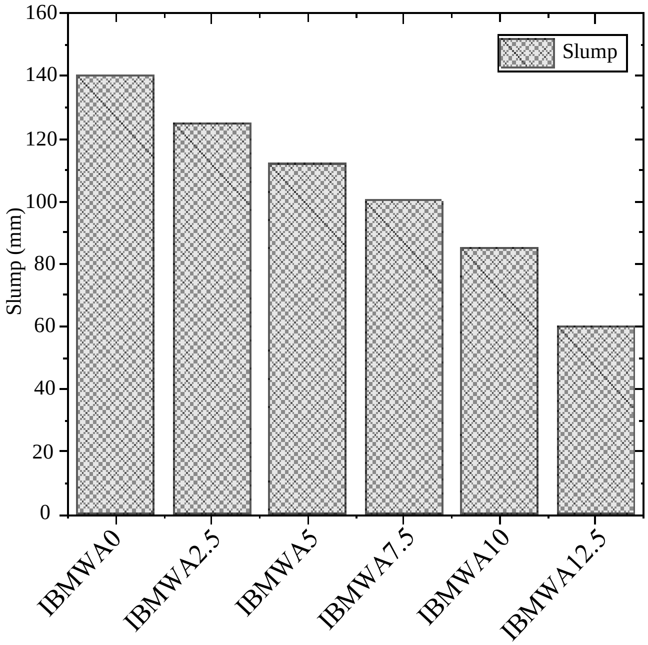

Fig. 5 Slump values of concrete with varying IBMW percentage

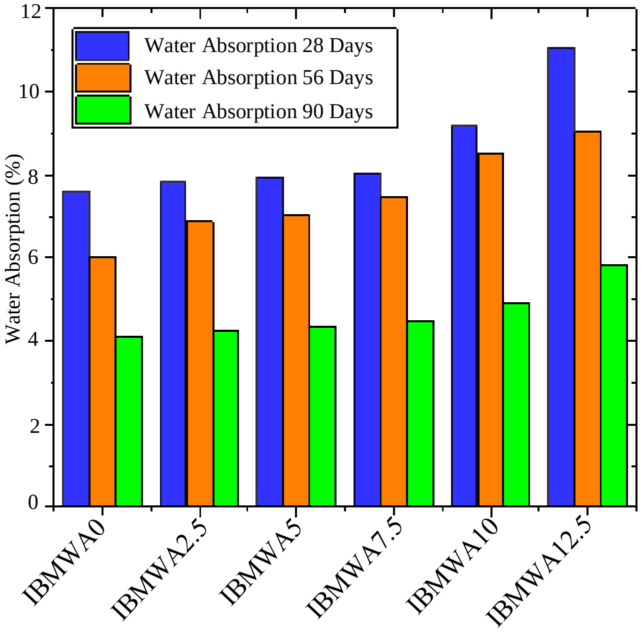

Fig. 6 Water absorption of concrete mixes containing IBMW

The primary controlling elements affecting concrete's porosity are IBMWA and the degree of porosity, along with the porosity of the concrete itself. The difference in water absorption with different IBMWA replacement percentages and curing ages is shown in Figure 6. Due to the porous structure of concrete, water absorption increases linearly with IBMWA concentration for a given curing day. The water absorption for a particular mix reduces as the number of curing days rises. This tendency may be caused by a rise in pozzolanic activity, which decreases pores and induces pore discontinuity due to the production of C-S-H gels. Additionally, it is evident that compared to the other mixes, IBMWA10 and IBMWA12.5 absorb significantly more water. This aligns with the sample workability results, demonstrating a marked decrease in a slump at these mixtures.

4.2. Density

Figure 7 shows the Saturated Surface Density (SSD) and Oven Dry Density (ODD) of all the mixes after 28 days of curing. These results are an average of three samples for each composition. The SSD for the control mix (IBMW0) was 2325 kg/m^3. For the replacement levels of 2.5, 5, 7.5, 10 and 12.5%, the SSD values were 2403 kg/m^3, 2516 kg/m^3, 2618 kg/m^3, 2701 kg/m^3 and 2798 kg/m^3 respectively. Similarly, the ODD for the samples at replacement levels of 2.5, 5, 7.5, 10 and 12.5% were 2374 kg/m^3, 2495 kg/m^3, 2574 kg/m^3, 2665 kg/m^3 and 2702 kg/m^3 respectively.

It becomes evident that as replacement levels rise, both SSD and ODD increase. Although, IBMWA content is anticipated to reduce density due to its porous nature. The rise in density values results from IBMWA's filler effect and minimal pozzolanic activity. Additionally, Wollestonite, a component of IBMWA, minimises pores [36], increasing density. As a result, it is discovered that ODD and SSD rise linearly with an increase in IBMWA content. However, a replacement level between 10 and 12.5% could not be practical because other concrete qualities, such as slump and water absorption, exhibit a sharp decline at such levels.

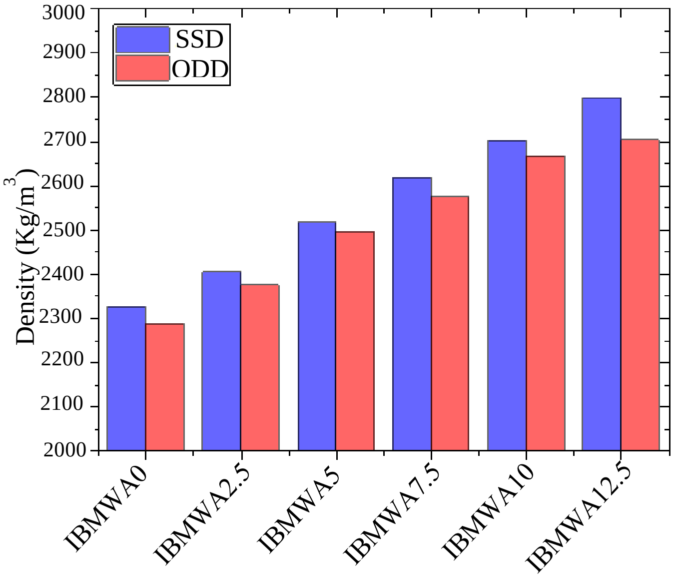

Fig. 7 Graph showing the SSD and ODD for concrete mixes containing IBMWA after 28 days of curing

4.3. Mechanical Characteristics

Figure 8(a) shows the typical compressive strength of concrete using IBMWA as a partial replacement for cement after 7, 28, 56, and 90 days of curing.

The average compressive strength at seven days was determined to be 22.32 MPa, 22.84 MPa, 23.11 MPa, 25.8 MPa, 23.87 MPa, and 22.1 MPa for IBMWA0, IBMWA2.5, IBMWA5, IBMWA7.5, IBMWA10, and IBMWA12.5. At 28 days, the equivalent values were 39.21 MPa, 38.57 MPa, 41.03 MPa, 46.02 MPa, and 41.66 MPa.

Furthermore, samples containing IBMWA experienced an increase in compressive strength over time. The average compressive strength values grew from IBMWA0 to IBMWA7.5 as the corresponding replacement levels increased, but the values decreased when the replacement levels were raised further.

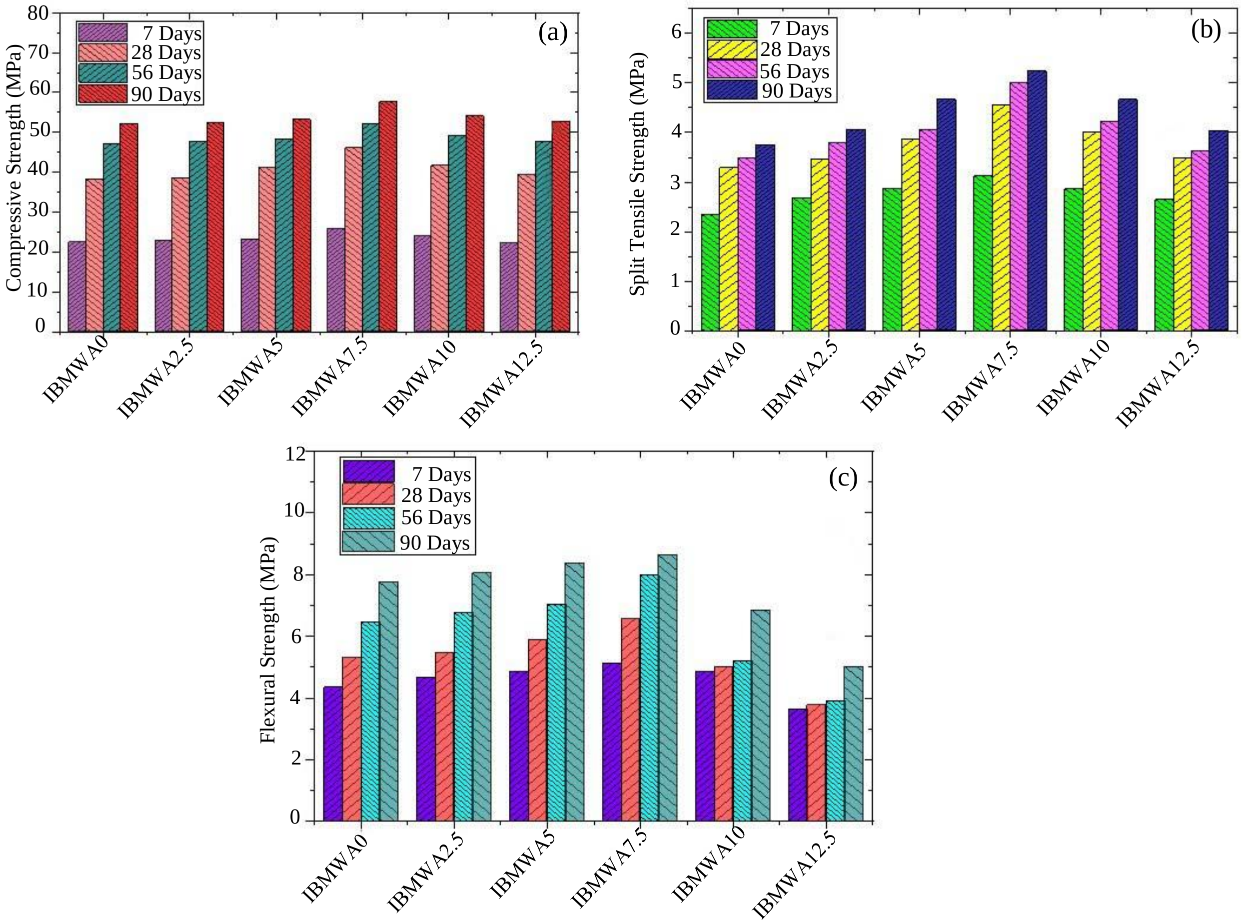

Fig. 8(a) Compressive strength, (b) Split tensile strength, and (c) Flexural strength (in MPa) for concrete mixes containing IBMWA after 7, 28, 56 and 90 days of curing.

Figure 8(b) displays the average split tensile strength values for three specimens for each composition at 7, 28, 56, and 90 days. All of the composition's 7-day deals fell between 2 and 4.5 MPa. The values over 28 days were 3.29 MPa, 3.47 MPa, 3.88 MPa, 4.55 MPa, 4.01 MPa, and 3.48 MPa.

The split tensile strength values for the mixes IBMW2.5, IBMW5.0, and IBMW7.5 increased during all the days; however, these values declined for IBMW10 and IBMW12.5. The percentage gains in strength over the previous 28 days at 56 days were 5.17, 8.65, 4.38%, 9.45, 4.99%, and 3.74%, respectively.

Likewise, the percentage increase in strength over the previous 28 days at 90 days was 13.68%, 16.43%, 19.85%, 14.73%, 15.97 5 and 15.52%, respectively. In the context of split tensile strength, IBMWA7.5 (9.45% for 56 days and 19.85% over 90 days) shows the most significant increase in power compared to the 28-day values. The results of the flexural strength tests conducted on beams at 7, 28, 56, and 90 days are shown in Figure 8(c).

Flexural strength values for IBMWA0, IBMWA2.5, IBMWA5, IBMWA7.5, IBMWA10, and IBMWA12.5 at 28 days are 5.29 MPa, 5.47 MPa, 5.88 MPa, 6.55 MPa, and 5.01 MPa, respectively. The 56-day strength shown an increase in each composition for each composition compared to the 28-day flexural strength of 22.11%, 23.77%, 19.90%, 21.83%, 3.99%, and 3.44%, respectively.

The percentage gain in power was also 46.31%, 46.98%, 42.01%, 31.60%, 36.73%, and 32.80% at 90 days. Thus, it can be shown that IBMWA2.5 has the most significant increase in flexural strength. Additionally, for all composition ranges, there is a noticeable improvement in strength gain at 90 days, with IBMWA10 and IBMWA12.5 showing the highest strength gains compared to the corresponding values at 56 days (36.73% and 32.80%, respectively, at 90 days compared to 3.99% and 3.44% at 56 days).

This suggests the ongoing hydration process, most likely due to the concrete's pozzolanic activity. Likewise, Flexural strength values reached peaks at a 7.5% replacement level, similar to compressive strength and split tensile strength. Several reasons [34] could be mentioned to describe the strength gain mechanism of concrete up to a replacement level of 7.5% and the decrease in values after that. These are mentioned as follows:

4.3.1. Filler Effect

As can be observed in the grain size distribution plot (Figure 1), all IBMWA particles are smaller than 1 mm, and over 89% of them pass through a 600-micron sieve, whereas 42% do so. As a result, a sizeable portion of the particles are in the excellent range. Such tiny particles efficiently fill pores, resulting in a denser microstructure.

However, these IBMWA particles start contributing as fine aggregates after the replacement levels surpass 7.5% because their function as filler materials is identified. Due to their porous nature, these particles absorb the water needed for hydration, which reduces the strength gained by IBMWA10 and IBMWA12.5. Additionally, voids tend to increase due to IBMWA's amorphous particle shape and tendency to operate as fine aggregates (i.e., following composition IBMWA7.5).

4.3.2. Pozzolanic Activity

The main components of IBMWA are silica, ferric oxide, alumina, wollestonite, and albite. Albite, alumina, ferric oxide, and silica are among those that actively contribute to the creation of C-S-H gel along with additional hydration products.

4.3.3. Wollestonite

This mineral has an aspect ratio of typically 3:1 to 20:1, is acicular in shape, and typically takes the form of fibre [42]. The use of this mineral in concrete may improve flexural strength due to its fiberous nature. Additionally, the mineral is said to cause pore discontinuity, which could improve the strength metrics. Additionally, the results of Soliman and Nehdi [38] imply that this mineral has a significant role in enhancing early-age compressive strength.

4.4. Ultrasonic Pulse Velocity

At 28, 56, and 90 days after curing, standard samples measuring 150 X 150 X 150 mm were subjected to this Non-Destructive Test (NDT). The pulse velocity was applied using the direct transmission approach. The specimen surface was cleansed, and then petroleum jelly was applied. This guaranteed that the probe and sample had a correct acoustic connection. The UPV measurements are said to be impacted by several things.

These include cement's strength characteristics, its physical qualities, the existence of pores, and the characteristics of coarse and fine aggregates, such as density, the presence of harmful components, the sample size, the measurement temperature, the moisture content, etc. These elements may lead to inconsistent outcomes.

The cubes were thus separated into 30 mm x 30 mm grids to prevent these variations. Three samples were tested for each composition, and the average values of the test results were reported to determine the calibre of the concrete samples. Figure 9 displays the findings.

The control mix's UPV value was discovered to be 4.22 km/s at 28 days, whereas the values at the other replacement levels of 2.5%, 5%, 7.5%, 10%, and 12.5% were 4.35 km/s, 4.48 km/s, 4.57 km/s, 4.62 km/s, and 4.68 km/s, respectively.

The UPV values for replacement levels of 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% at 56 days were 4.45 km/s, 4.75 km/s, 4.98 km/s, 5.06 km/s, 5.14 km/s, and 5.32 km/s. For replacement levels of 0%, 2.5%, 5%, 7.5%, 10%, and 12.5%, respectively, these values climbed to 4.65 km/s, 4.78 km/s, 4.89 km/s, 5.12 km/s, 5.23 km/s, and 5.39 km/s at 90 days.

Thus, it may be concluded that the values of UPV on any given day grow as replacement levels rise. Additionally, given a specific mix composition, the UPV values increase as the number of days rises. Compared to UPV values from 28 days prior, IBMWA12.5 showed the most significant percentage rise in UPV values. For IBMWA12.5, the 56-day and 90-day UPV values were 13.67% and 15.17%, respectively, more important than the corresponding 28-day values.

This increased UPV value with higher replacement levels at specific curing days (28, 56, and 90 days) may be due to IBMWA's filler effect, which improves the concrete's quality. The synergistic combination of pozzolanic activity and the filler effect causes the increase in UPV levels as the number of days increases.

Wollestonite mineral also causes pore discontinuity, improving concrete homogeneity and quality [42]. The composition ranges IBMWA7.5, IBMWA10, and IBMWA12.5 are classified as having "Excellent Quality of Concrete" since their UPV values are consistently higher than 4.5 km/s on all days.

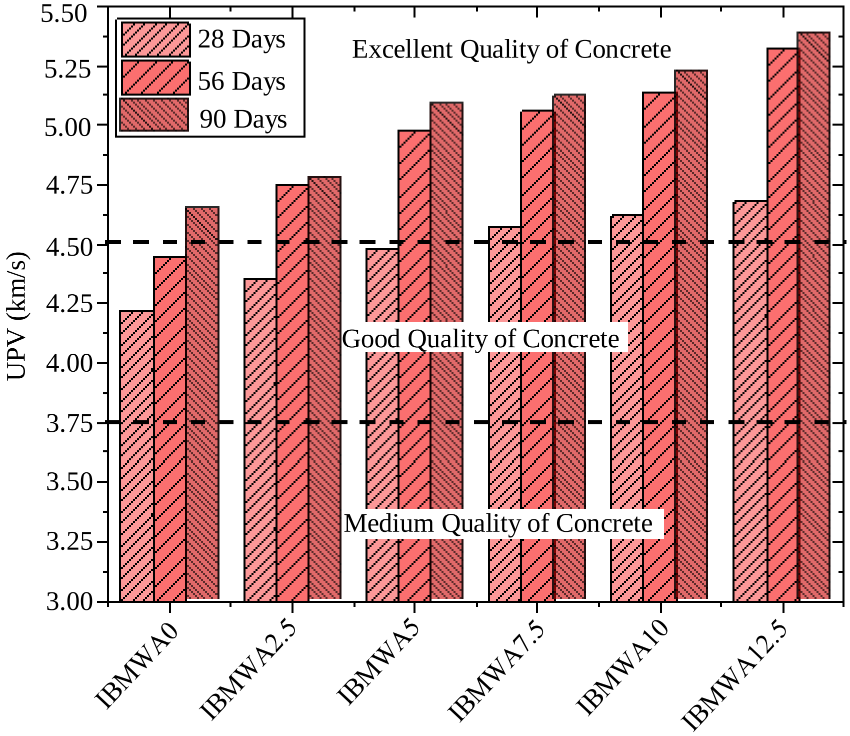

Fig. 9 UPV results for various replacement levels after 28, 56 and 90 days of curing

4.5. Drying Shrinkage

With varying percentages of IBMWA substitution, Figure 10 shows the drying shrinkage of concrete after 28 days, 56 days, 90 days, 112 days, and 365 days. After being formed for 24 hours, the three layers of prisms were removed. With an accuracy of 0.001 mm per division, dial gauge extensometers were used to measure length variation. IBMWA and its porous makeup mostly cause the drying shrinkage of concrete.

The drying shrinkage in the current work exhibits a proportional correlation with the cement replacement level with IBMWA. Drying shrinkage values ranged from 489 to 610 microstrain. Compared to those without IBMWA, the drying shrinkage in the prisms containing IBMWA was 10–20% higher. The experimental finding demonstrates that rising IBMWA content causes drying shrinkage values to grow at any replacement level.

The shrinkage findings after 28 days of drying varied between $500x10^{-6}$ and $575x10^{-6}$ for all mixes, $519x10^{-6}$ to $579x10^{-6}$ during 56 days, $525x10^{-6}$ to $592x10^{-6}$ during 56 days, and $532x10^{-6}$ to $598x10^{-6}$ during 112 days, respectively. For the first 28 days, the measured drying shrinkage levels are more significant and continue to slow down over the following days [41]. The hydration rate affects the drying shrinkage values. Since IBMWA exhibited pozzolanic activity in this study, its addition increased hydration, increasing drying shrinkage. With rising replacement levels, the drying shrinkage values rose. The presence of IBMWA's porous nature, which causes drying shrinkage to rise as the percentage of IBMWA increases, is the most likely cause of these phenomena. The IBMWA particles collect moisture and eventually release water particles, causing the concrete to shrink. The findings of the other researchers support the same patterns.

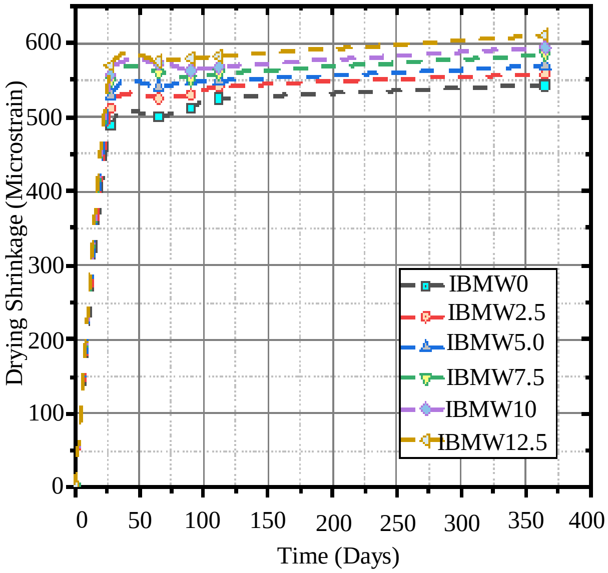

Fig. 10 Drying shrinkage values results for various replacement levels after 28, 56 and 90 days of curing

Additionally, it is clear that most drying shrinkage occurs in the first three months, after which the values are discovered to be constant. Figure 11 shows the impact of IBMWA replacement levels on concrete drying shrinkage values for 28, 56, 90, and 112 days. The statistics for a year are not considered because they were essentially consistent. A linear relationship exists between drying shrinkage values (ε) and IBMWA content (x). All R2 values are more than 0.95, which denotes a linear relationship.

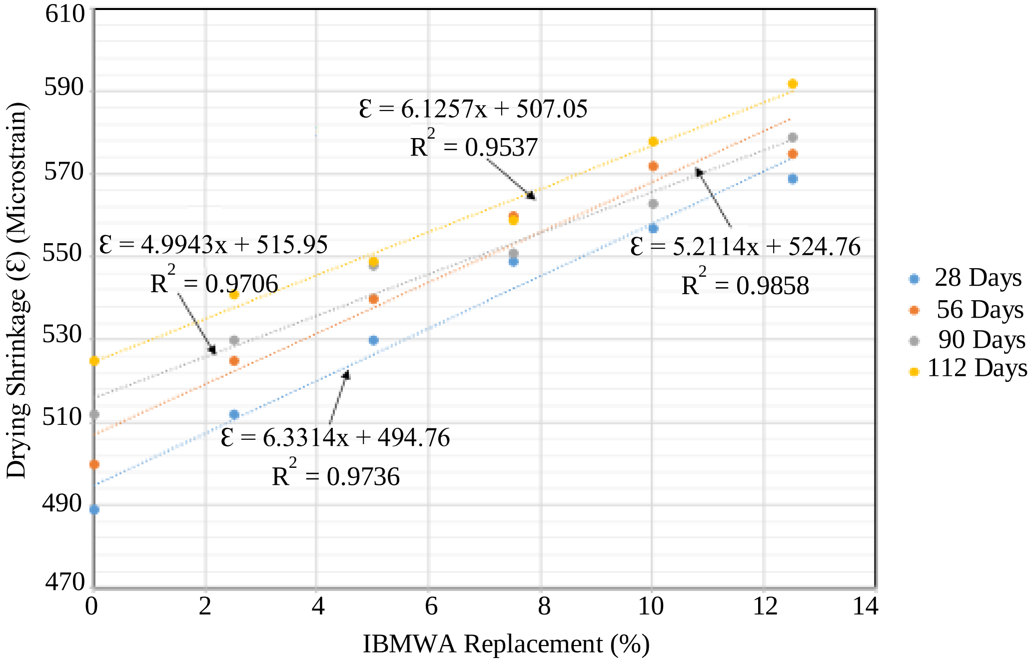

Fig. 11 Relation between drying shrinkage values at various replacement levels after 28, 56, 90 and 112 days of curing

4.6. Micro-Characterisation

Using a Hitachi S-3400N SEM with an EDS probe with a diameter of 2 m, micro-characterisation of the 28-day-cured specimens of compression testing sample was done to understand better the potential mechanism of improvement in mechanical and durability attributes up to 7.5% replacement levels. A 15 kV accelerating voltage was employed. 50 nA was the probe current used to analyse the chemicals.

As the IBMWA content increases, each sample's Back Scatter Electronic Image (BSEI) is shown in Figure 12 (a–f). To enable an assessment of microstructure at an identical magnification, all the photos were taken at a resolution of 2 m. The microstructure of the control mix (IBMWA0) is shown in Figure 12(a), which primarily consists of calcium oxide, C-S-H gel, and anhydrous cement. Additionally, significant micropores were found. The microstructure of concrete using IBMWA demonstrated significant variations from the control mix (IBMWA0).

For instance, up to a replacement level of 7.5%, the micro-pores decreased compared to the control mix, more C-S-H gels and calcium hydroxides were produced, and Ettringite was detected by EDS spot analysis. The end outcome was an enhanced dense microstructure. The existence of Wollensite, which is said to improve early strength parameters, create pore discontinuity, and give a denser microstructure [40], may be to blame for this. The studies also mentioned Wollensite's alkaline nature, which is a determining factor in enhancing reinforced concrete's corrosion resistance. The current research's findings support these conclusions. Figure 12(b) and (c) show the microstructure of IBMWA2.5 and IBMWA5 respectively.

In addition to the compounds in the control mix, acicular crystals of Wollensite are present in both images. Although more amounts of micro-pores could be found in the case of IBMWA5, the strength and durability results showed an improvement compared to the control mix. This contradictory result could be justified through the following aspects:

- The micro-pores are very small, and the values of strength, density and UPV justify the excellent quality of the resulting concrete.
- This could be possibly due to the denser microstructure, which is assisted by Wollensite, as reported by Kalla et al. [42].
- Kaur et al. [29] reported the formation of a denser microstructure at the composition IBMWA5, with the formation of rich, compact C-S-H gel and excellent bond.

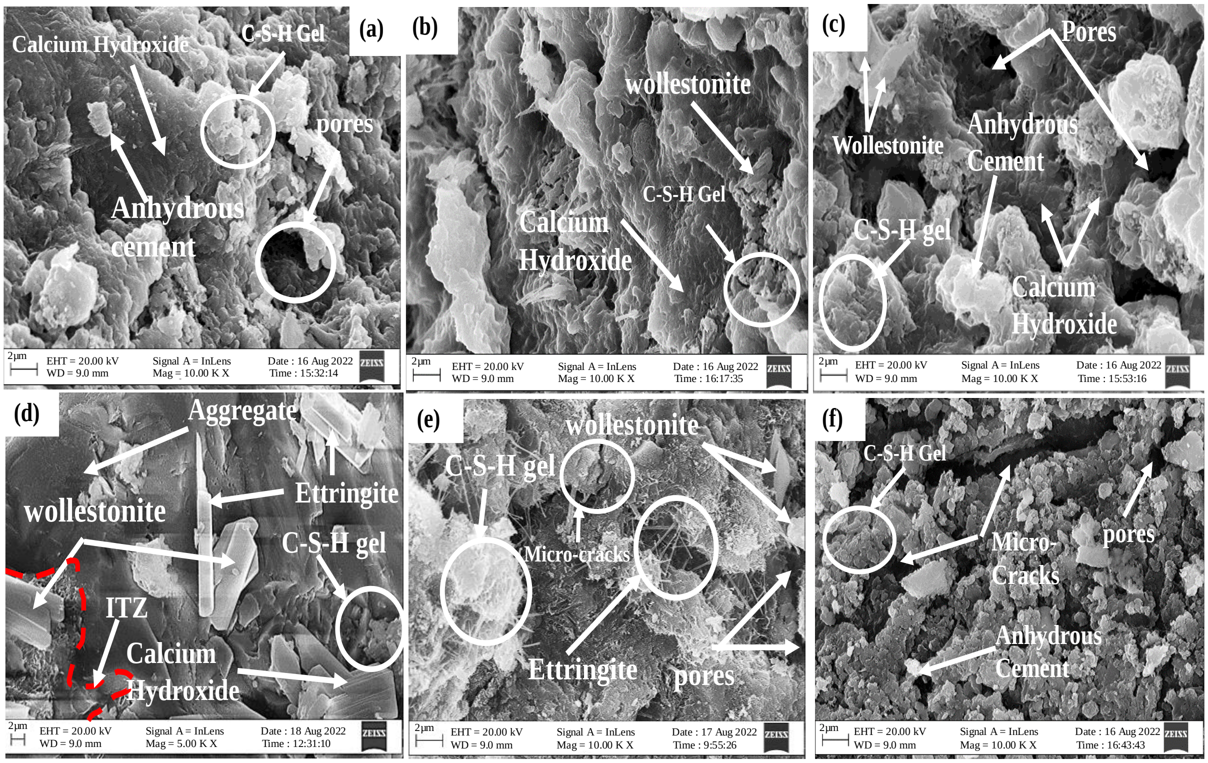

Fig. 12 (a-f) microstructure of concrete incorporating IBMWA for various replacement levels after 28 days of curing

Figure 12(d) presents the back scatter electron image of IBMWA7.5. It consists of Wollensite, Calcium Hydroxide, C-S-H gel, anhydrous cement and nominal amounts of Ettringite. The micro-pores are generally minimal, and a strong aggregate-mortar bond is seen at the I.T.Z. This justifies the attainment of maximum strength values at this composition.

Significant pores and micro-cracks are visible. The presence of larger quantities of sulphates and alkalis resulted in the formation of needle-like crystals of Ettringite, visible in IBMWA10 (Figure 12(e)). Kaur et al. [29] also reported that this composition resulted in porous and loss of microstructure. A reduction in strength parameters was noted due to the following possible reasons:

- The formation of large amounts of Ettringite caused a reduction in the formation of C-S-H gel.
- The excessive quantities of IBMWA resulted in more porous concrete, resulting in reduced slump, strength and density and higher water absorption values.

The highly porous and loose microstructure is obtained in the case of IBMWA12.5 (Figure 12(f)). This shows the presence of excess quantities of IBMWA. This results in the reduction of C-S-H gel formation. The magnitude of micro-cracks and micro-pores is also seen to increase significantly. The combined effect of reduced C-S-H gel, micro-cracks and micro-pores results in poor performance IBMWA12.5. These are consistent with the results of slump and strength values.

5. Conclusions

The present research describes the application of IBMWA in concrete with partial replacement of cement at levels 0 %, 2.5%, 5%, 7.5%, 10% and 12.5%. Based on this research, several interesting observations could be made and are presented below:

- IBMWA consists of Albite, Wollestonite, Alumina, Silica and Ferric Oxide. These compounds play a significant role in the properties of concrete incorporating IBMWA.
- Wollestonite is a critical mineral in IBMWA, which modifies the concrete properties incorporating IBMWA. It provides early strength, pore discontinuity and denser microstructure, affecting all the properties discussed in this paper.
- Concrete slump value decreases with increased IBMWA replacement levels due to the rise in water demand of porous IBMWA particles, causing a cohesive, sticky and harsh matrix.
- Water absorption increases linearly with an increase in replacement levels at 28, 56 and 90 days. For a particular composition of the mix, as the number of days increases, water absorption decreases due to a reduction in pores by hydration.
- Saturated Surface Density and Oven Dry Density increase with replacement levels.
- Compressive strength, Split tensile strength, and flexural strength measured at 7, 28, 56 and 90 days showed an optimum value of 7.5% replacement level of IBMWA.

The reasons identified were the filler effect, pozzolanic activity and the presence of Wollestonite mineral.

- The UPV values at 28, 56 and 90 days increased with an increase in replacement levels for all days.
- The microstructural findings using SEM-EDS are consistent with the results of the tests mentioned above and the literature.
- Thorough investigations should be carried out for the durability aspects of concrete incorporating IBMWA, as this provides a sustainable solution for waste disposal.

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