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ARTICLE

Experimental Investigation on the Structural and Economic Feasibility of Light-Transmitting Concrete Using Industrial By-Products

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ABSTRACT

The cement manufacturing process emits significant greenhouse gases and consumes substantial energy. The current situation demands alternative sustainable materials to cement in concrete production. On the other hand, rapid urbanization has led to the vertical expansion of modern structures, worsening daylight loss on lower floors, where artificial lighting is now essential. Innovative construction materials that enhance natural illumination are needed due to the energy crisis. A promising approach is light-transmitting concrete, which uses resin matrices, optical fiber, or polymer rods as light-guiding media. In the present study, plastic optical fiber was used as a light-transmitting material in the concrete. This study demonstrates the potential use of industrial by-products, including ground granulated blast furnace slag (0%, 10%, 20%, 30%, 40%) and micro silica (0%, 5%, 10%, 15%, 20%), as effective pozzolanic materials as cement substitutes in concrete to study the strength and durability properties of concrete experimentally. The economic and ecological feasibility of different concrete mix proportions was investigated. The optical fiber (1%) with the optimized percentage of industrial wastes, i.e., slag (20%) and micro silica (10%), was used in the concrete to study different properties of light-transmitting concrete. Results showed that the incorporation of industrial wastes with optical fiber (1%), used in the light-transmitting concrete, improved the performance and produced sustainable end products compared to the conventional concrete.

Keywords: Light Transmitting Concrete; Industrial Wastes; Strength; Economic Analysis; Performance Evaluation

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1. Introduction

Urbanization is rapidly increasing the demand for artificial lighting, markedly increasing energy consumption in buildings, and worsening global warming. It is essential to tackle this issue by emphasizing architectural and material techniques that optimize natural light use, thereby reducing reliance on artificial lighting and improving human health. Conventional methods use materials such as tempered glass, glass blocks, or clear polymers to facilitate the entry of natural light. Nevertheless, these materials often provide insufficient thermal insulation and do not effectively regulate the intensity of direct sunlight. In tropical regions, the inability of these materials to block direct sunlight necessitates the use of curtains in both residential and commercial environments, diminishing their energy-saving potential and increasing air conditioning energy consumption due to their poor insulating properties. In this context, light-transmitting concrete (LTC), an innovative type of concrete, presents a viable option. In contrast to fully transparent materials, LTC enables modulation of light-transmitting functional elements, thereby improving regulation of sunlight and optimizing illumination across various environments. Moreover, concrete provides enhanced resilience to impacts and storms, as well as better insulating properties than glass or plastic. LTC is multifunctional and used in infrastructure components such as sidewalks, road markings, speed bumps, staircases, and tunnels [1].

The development of light-transmitting concrete (LTC) marks a significant change in construction technology. It offers a unique blend of strength and aesthetic appeal that addresses practical and environmental issues. Light-transmitting concrete arose from the urgent need to reduce energy use in buildings while maintaining structural performance. Traditional concrete buildings, despite their strong mechanical properties, have limitations in their use of natural light. This limitation leads to a greater reliance on artificial lighting, which significantly contributes to global energy consumption. In fact, building operations are responsible for around 28% of global CO_2 emissions each year [2]. LTC is a novel material developed in recent decades. It allows light to propagate through optical fibers embedded in opaque concrete. LTC enhances aesthetic value and significantly reduces energy use by providing natural light to buildings, thereby improving indoor daylighting. Research has demonstrated that sunlight, a sustainable light source compared with artificial lighting, creates a more enjoyable atmosphere and promotes a better work environment, thereby enhancing productivity [3]. The LTC technology provides a creative solution that connects structural needs with energy efficiency. Light-transmitting concrete uses translucent materials, such as optical fibres, glass aggregates, or polymer resins, in the concrete mix to allow light to pass through while maintaining the material's strength [4]. Optical fibres are the most frequently used transparent materials for LTC production, owing to their superior light transmittance capabilities achieved through total internal reflection [5,6]. The compressive strength increases with increasing POF ratios because the loading machine is oriented perpendicular to the POF arrangement, which is maintained at a consistent spacing within the cubic specimens [7]. The incorporation of optical fiber and resin into light-transmitting concrete reduced electricity consumption. Polymethyl methacrylate tubes increased the illumination energy efficiency [8]. Chiew et al. [3] developed an artificial neural network model to predict the light transmittance of the light-transmitting concrete. The use of 1 mm-diameter optical fibre increased the strength of concrete; however, it reduced the strength of LTC [3]. The addition of optical fibre to self-compacting concrete increased the compressive and tensile strength of the light-transmitting concrete [9]. The strength of LTC increased with the increase in the percentage of optical fibre [10]. The optical fibre of 1 mm diameter increased the strength of concrete; afterwards, it reduced the strength of LTC [11]. Mbabazi et al. [12] investigated the mechanical and optical properties of light-transmitting foamed concrete (LTFC) composites. The vertical arrangement of optical fiber enhanced the compressive strength, while the horizontal fiber arrangement increased the flexural strength of LTFC. LTFC reduces thermal conductivity, thereby enabling daylighting and mitigating urban heat. Shen et al. [13] investigated the properties of light-transmitting concrete containing a PMMA rod. Results showed that LTC walls increased average daily illuminance and strong thermal adaptability.

The rapid urbanization and the widespread use of concrete have led the construction industry to place a strong emphasis on alternative materials to achieve sustainability and reduce carbon dioxide emissions. However, the cement and concrete industries are among the most significant contributors to global carbon dioxide (CO_2) emissions, largely due to the widespread use of Ordinary Portland Cement (OPC). To minimize the environmental impact, many Low-Carbon Concrete (LCC) mixtures have been developed with supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag (GGBFS), fly ash (FA), silica fume (SF), and nanomaterials. When used as OPC replacements, these materials reduce CO_2 emissions and enhance the mechanical properties, crack propagation resistance, toughness, and overall durability of concrete. Because of its positive environmental impact and sustainability, incorporating recycled or waste materials into concrete is considered the most advantageous approach [14]. Blast furnace slag is a byproduct of steel or iron manufacture. GGBFS is chemically identical to Portland cement with different concentrations of lime, silica, and alumina. The GGBFS characteristics are influenced by the types of ore, flux, and charged coke, as well as contamination. Slag from iron extraction can be converted to lumps that harden on cooling but have no cementitious properties, or sand-like granules by rapid quenching and grinding to retain pozzolanic properties and avoid crystallization [15]. Micro silica is a very fine powder consisting mainly of amorphous silicon dioxide. It is a waste product from the silicon and ferrosilicon industries.

The incorporation of various industrial wastes into concrete reduces the demand for natural resources, thereby offering environmental benefits [16]. Also, the incorporation of industrial waste into light-transmitting concrete. SF increased compressive strength while reducing permeability due to its ultra-fine particles [17,18]. Chinchillas-Chinchillas et al. [19] observed that incorporating 10% SF resulted in denser pervious concrete without any improvement in strength characteristics, which may be attributed to the dissolution of calcium hydroxide (CH) due to underwater curing [20]. The incorporation of SF up to 10% positively affected the performance of pervious concrete [21]. Blast furnace slag (BFS) predominantly affected early-age strength, but the enhanced later-age strength may be attributed to its slow hydration rate [22].

This study investigates the compressive strength (CS) of 100 mm cube specimens of concrete consisting of industrial wastes, i.e., GGBFS by 0%, 10%, 20%, 30%, 40%, and micro silica (MS) by 0%, 5%, 10%, 15%, 20% as cement substitution, by both destructive and non-destructive testing methods at 7, 28, 90, and 150 days. The dynamic modulus was determined at 28 days. The optimal contents of industrial wastes, i.e., GGBFS and MS, were added to the light-transmitting concrete (LTC) to study their impact on LTC. A study of the economic and environmental effects of various concrete mixes was conducted. The present study focuses on the combined optimization of industrial waste materials (GGBFS and micro silica) with the optical fiber (1%), specifically for light-transmitting concrete. The novelty of this work lies in integrating material optimization with functional performance (light transmission), mechanical properties, and environmental impact assessment within a single framework.

The novelty of the present study lies in the development of sustainable LTC by incorporating industrial waste materials, such as GGBFS and Micro Silica, as well as plastic optical fibers. The study not only evaluates the light transmission characteristics of LTC but also investigates its mechanical and durability performance. In addition, the long-term behavior of the concrete was studied up to 150 days, including sulfate resistance analysis. The use of industrial by-products as a partial cement replacement also makes the developed LTC more sustainable and environmentally friendly than conventional concrete.

2. Methodology

The present work utilized 43-grade Ordinary Portland cement conforming to IS: 8112 [23]. The physical and chemical properties of the cement are presented in **Tables 1** and **2**. Coarse sand was used as the fine aggregate, while gravel with a maximum size of 10 mm was utilised as the coarse aggregate, conforming to IS: 383 [24] and with properties given in **Table 3**. In this study, 10 mm coarse aggregates were used because smaller aggregates facilitate proper placement of optical fibers and improve light transmission through the concrete. Tap water was used for casting and curing the specimens. Industrial byproducts, i.e., MS and GGBFS, were utilized as cement substitutes in concrete production. MS was used at 0%, 5%, 10%, 15%, and 20%, whereas GGBFS was included at 0%, 10%, 20%, 30%, and 40% by weight of the cement. The plastic optical fiber was used at 1% in the concrete [25]. The materials used in this study, namely plastic optical fiber (POF), GGBFS, and micro silica (MS), were selected after a detailed review of prior research. The literature indicates that plastic optical fiber offers better light transmission than other materials, such as glass fiber and resin. The micro silica (MS) and GGBFS were procured from a local supplier. The MS was grey in color, had a particle size of 45 microns, and a specific gravity of 2.06. GGBFS was off-white in color, with a fineness of 2.2 and a specific gravity of 2.87. The chemical composition of used industrial wastes is given in **Table 2**. The microstructural characterization of cement and industrial wastes, ie., GGBFS and MS, was studied using SEM and EDS, and the results are illustrated in **Figure 1**. The properties of the optical fiber are given in **Table 4**. The mix details of concrete containing industrial wastes, i.e., GGBFS and MS, are given in **Table 5**.

Table 1. Physical Properties of Cement.

Property	Consistency	IST (min.)	FST (min.)	Fineness	CS at 7 Days	CS at 28 Days
Value	29.5%	135	245	4%	24.2 MPa	44.5 MPa

Table 2. Chemical Properties of Cement.

Materials	CaO	SiO_2	Al_2O_3	Fe	MgO	Na_2O	K_2O	Loss on Ignition
Cement	60.3	21.43	5.9	4.8	2.65	0.65	1.1	-
GGBFS	35.38	35.20	18.80	1.30	6.93	0.58	-	0.20
MS	-	90	-	-	-	0.87	-	2.65

Table 3. Physical Properties of Aggregates.

Sr. No.	Property	Sand	Gravel
1	Zone	II	-
2	Water absorption	2.5	2.9
3	Fineness Modulus	3.1	6.5
4	Specific Gravity	2.61	2.72

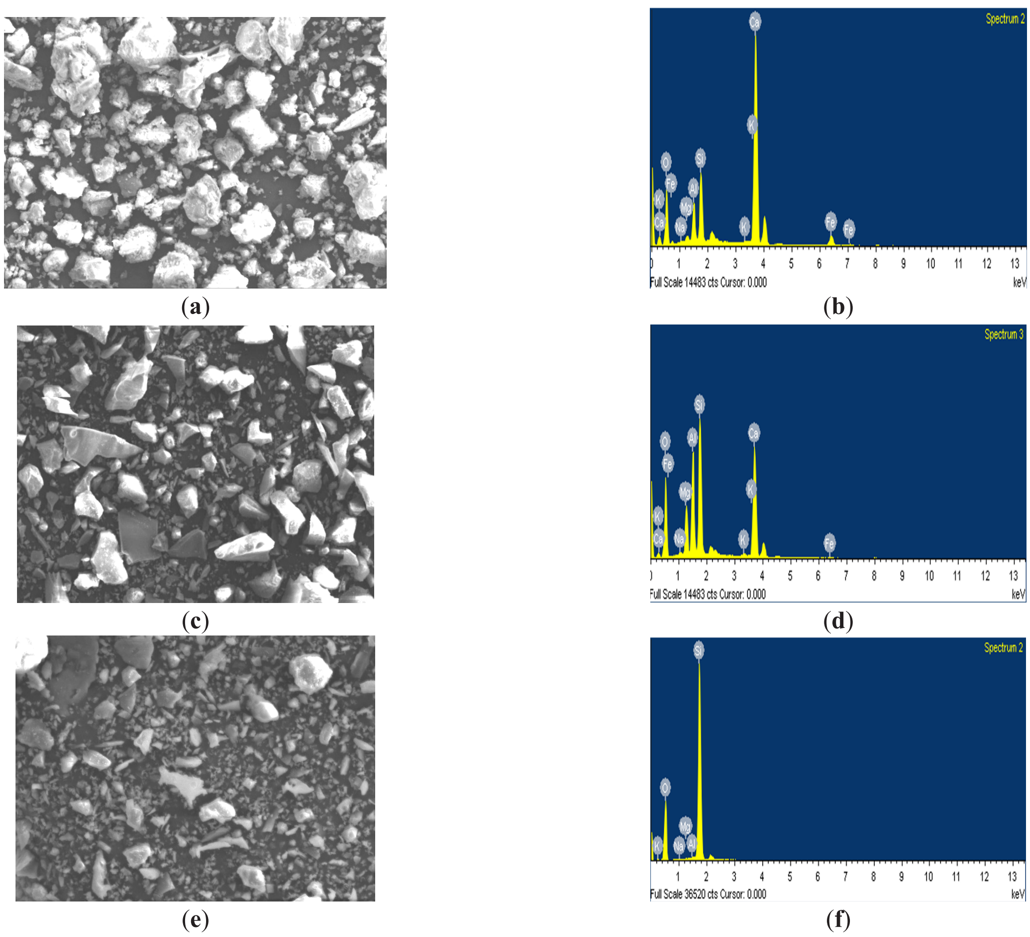

Figure 1. Cement (**a**) SEM micrograph; (**b**) EDS image, GGBFS; (**c**) SEM micrograph; (**d**) EDS image, Micro silica; (**e**) SEM micrograph; (**f**) EDS image.

Table 4. Properties of Optical Fiber [25].

Sr. No.	Property	Value
1	Material	Plastic
2	Diameter	0.75 mm
3	Cladding material	Methyl methacrylate (MMA)

Table 5. Mix Designation of Different Mixtures.

S. No.	Mix No.	Quantities in kg/m^3					
		Cement	Sand	Gravel	Water	GGBFS	MS
1	IW0	390	944	1,026	187.2	0	0
2	IW1	351	944	1,026	187.2	39	0
3	IW2	312	944	1,026	187.2	78	0
4	IW3	273	944	1,026	187.2	117	0
5	IW4	236	944	1,026	187.2	156	0
6	IW5	370.5	944	1,026	187.2	0	19.5
7	IW6	351	944	1,026	187.2	0	39
8	IW7	331.5	944	1,026	187.2	0	58.5
9	IW8	312	944	1,026	187.2	0	78

The casting and testing of cubic specimens of concrete of size 100 mm containing industrial waste at different percentages were carried out as per IS:516-1989 at 7, 28, 90, and 150 days, as shown in **Figure 1b,c**. The carbon emissions and cost of the different mix proportions were evaluated [26]. The optimal contents of GGBFS and MS will be used in light-transmitting concrete to study its mechanical and durability properties as shown in **Figure 2**. Optical fiber at an optimum content of 1% was added to the LTC [25]. The details of optimized mix proportions with optical fiber are given in **Table 6**. The compressive strength at 7, 28, 90, and 150 days and the light transmittance of the light-transmitting concrete were determined at 28 days for the optimized LTC mixtures.

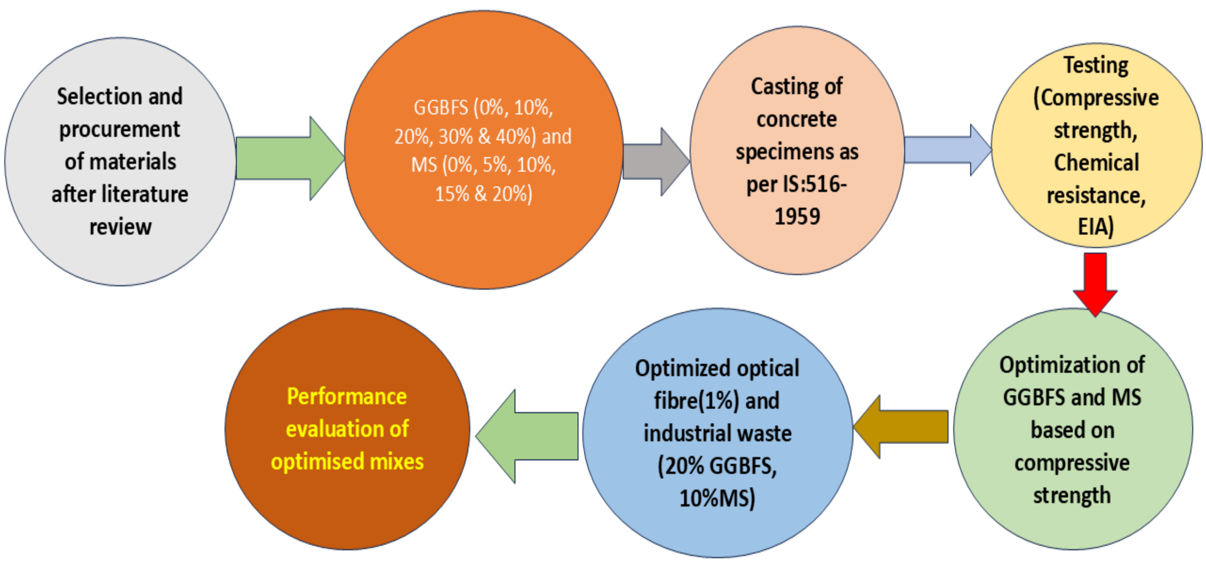

Figure 2. Methodology Adopted for Experimentation.

Table 6. Mix Designation of the Optimized Mix, kg/m^3.

Sr. No	Mix No.	Cement, kg/m^3	Sand, kg/m^3	Gravel, kg/m^3	Water, kg/m^3	Optical Fiber (%)	GGBFS, kg/m^3	MS, kg/m^3
1	OM0	390	944	1,026	187.2	0	0	0
2	OM1	390	944	1,026	187.2	1	0	0
3	OM2	312	944	1,026	187.2	1	78	0
4	OM3	351	944	1,026	187.2	1	0	39

The photo of the plastic optical fiber is shown in **Figure 3**. The fiber was oriented horizontally. The size of the specimen was 10 cm, and the spacing of the fibers was 2 cm. The optical fiber was inserted in four rows in one direction (horizontal) in the cube specimens, as shown in **Figure 4**. The wooden specimens were oiled to facilitate their removal from the mould, and the specimens after casting are shown in **Figure 5**. The fibers were passed through the inserted holes only in the horizontal direction. The hole diameter varied with the volume of the optical fiber, while the hole spacing was kept constant, as shown in **Table 7**. The concrete was poured in thin layers and compacted gently between the layers, which minimizes the fiber displacement due to the placement of concrete in the mould. The three specimens were cast for each test, and the average value of the three specimens was used to obtain the final results for each parameter, i.e., compressive strength, elastic modulus, light transmittance, and chemical resistance of the concrete mixes.

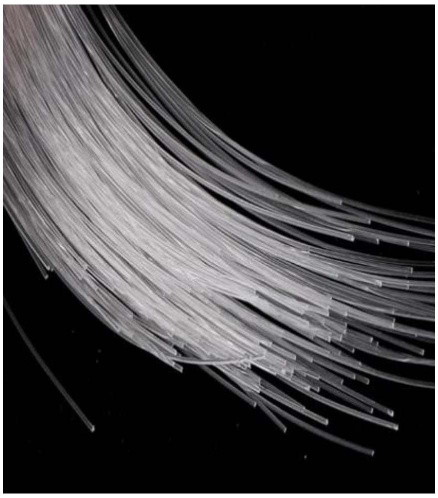

Figure 3. Plastic Optical Fiber.

Figure 4. Casting of Concrete Specimens.

Figure 5. Compressive Strength Testing of LTC Specimens.

Table 7. ECO_2, and Cost of Raw Materials [26].

Materials	Cement	Sand	Gravel	Water	Optical Fiber	MS	GGBFS
ECO_2, $kgCO_2e/kg$	0.93	0.0051	0.0008	0.0008	72.92	0.02	0.08
Cost, INR/kg	7	1	1.8	0.05	7,000	8	4

In the present work, a 40 W white bulb was used to measure the light-transmitting ability of different LTC mix proportions, as shown in **Figure 6**. The light source was kept 10 cm from the specimens to ensure uniform illumination of the concrete cube's surface. The Sigma Instruments 101 Digital Lux Meter was used to measure the light transmittance of concrete. External sources were not present in the lab room to avoid disturbance of the results during experimentation [25].

The chemical resistance of concrete from different mixes was determined by measuring the change in compressive strength after exposure to a sulfate solution for a specified period. The chemical resistance was measured in accordance with ASTM C1012/C1012M [27]. Magnesium sulfate at 5% mass was used during solution preparation. Cube specimens were immersed in this solution, then cured for 28 days in water, and were removed and tested at the required ages. After 28 days of normal water curing, the specimens were immersed in a magnesium sulfate solution for 7, 28, and 62 days. Therefore, the total testing duration became 35 days (28 + 7 days), 56 days (28 + 28 days), and 90 days (28 + 62 days).

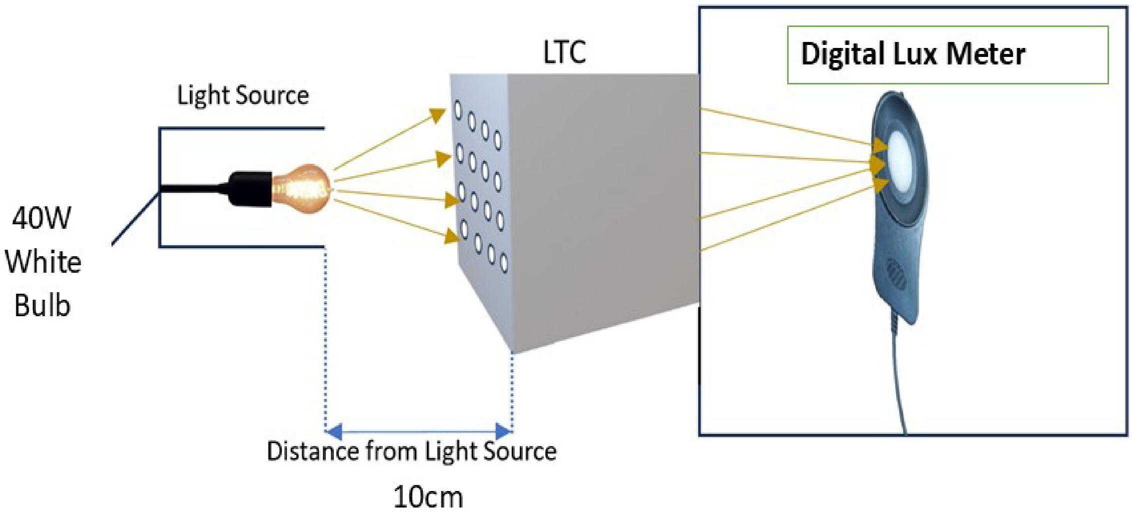

Figure 6. Methodology Adopted for Light Transmittance of Concrete Specimens [25].

The microstructural characterization was conducted to examine the shape and elemental composition of mortar specimens. Scanning Electron Microscopy (SEM) was employed to examine the microstructure of cement composites. Scanning Electron Microscopy (SEM) employs a focused electron beam to scan a surface, producing an image. The electrons interact with the sample, generating diverse signals that provide insights into the surface topography and composition. These signals provide information about the sample, including exterior morphology (texture), chemical composition, and the crystalline structure and orientation of the constituent materials. SEM is employed to discern phases through qualitative chemical analysis and examination of crystalline structure. SEM micrographs convey data regarding topography, morphology, and composition. The embodied CO_2 and cost of the various concrete mixtures were evaluated. The values of cost and embodied carbon for the different concrete materials are given in **Table 7** [26,28–30].

To develop the best-suited mixtures that meet the desired performance standards, the performance index (PI) tool encourages the identification of additive content. In place of qualitative terminology, quantitative analysis can be used to describe the performance of additives in concrete. If the performance of plain concrete is considered to be 1.0, then the performance of concrete that contains additives will be either less than or more than 1. This indicates that the performance of concrete with additives is either inferior to or superior to that of the plain mix in many respects. According to Kayali and Ahmed [31], the performance of additives such as GGBFS and MS will be assessed individually before being compared with that of the plain concrete mix. The performance index was evaluated using the following formula given in Equation (1). The parameters, such as compressive strength, dynamic modulus, cost, and carbon emissions, of different concrete mix proportions were compared with those of concrete without any additives.

$$\text{Performance index} = \frac{\text{Parameter of concrete containing additives}}{\text{Parameter of concrete without any addtitves}}. \quad (1)$$

3. Results and Discussion

3.1. Compressive Strength

The CS of concrete specimens consisting of MS and GGBFS was experimentally evaluated at 7, 28, 90, and 150 days under water-curing conditions. A change in the CS of the concrete was observed in **Figure 7**, and the addition of industrial wastes, specifically MS and GGBFS, initially increased the CS by a certain percentage; thereafter, the CS declined. The gain in concrete strength with the incorporation of micro silica was noted, likely attributable to their smaller particle size, which occupies voids and compacts the matrix [15,17,21,32,33]. The use of GGBFS enhanced the CS of the concrete at every curing age, which may be due to the pore-filling effect and the pozzolanic reaction.

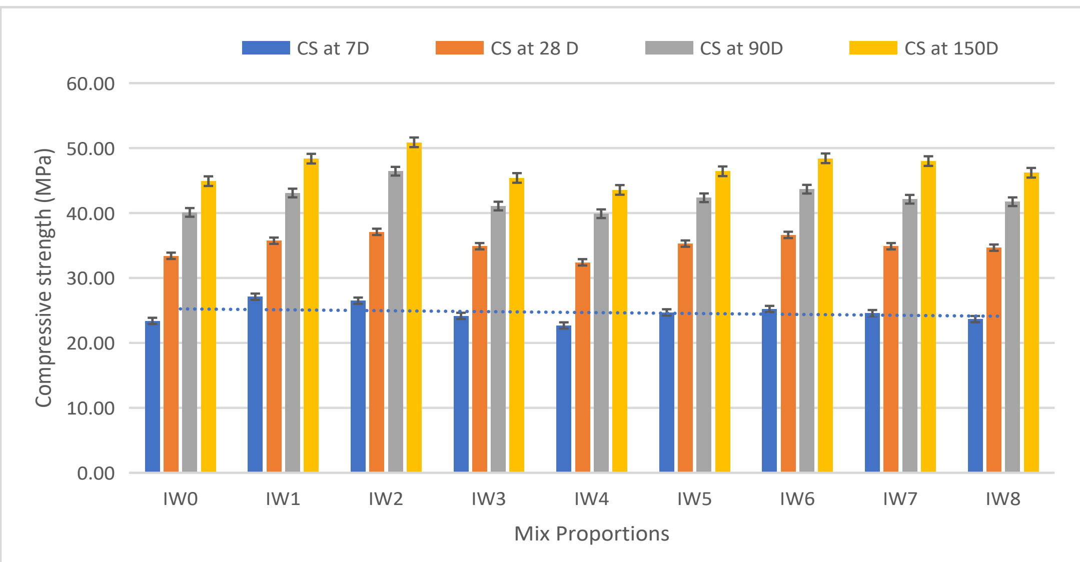

Figure 7. Variation of Compressive Strength of Different Concrete Mixtures.

The CS of the concrete ranged from 23.4 MPa to 26.50 MPa, 32.4 MPa to 37.8 MPa, 39.89 MPa to 46.44 MPa, and 43.4 MPa to 50.89 MPa at 7, 28, 90, and 150 days, respectively. The optimum proportions of MS and GGBFS for maximizing CS were 10% and 20%, respectively, as given in **Figure 8**.

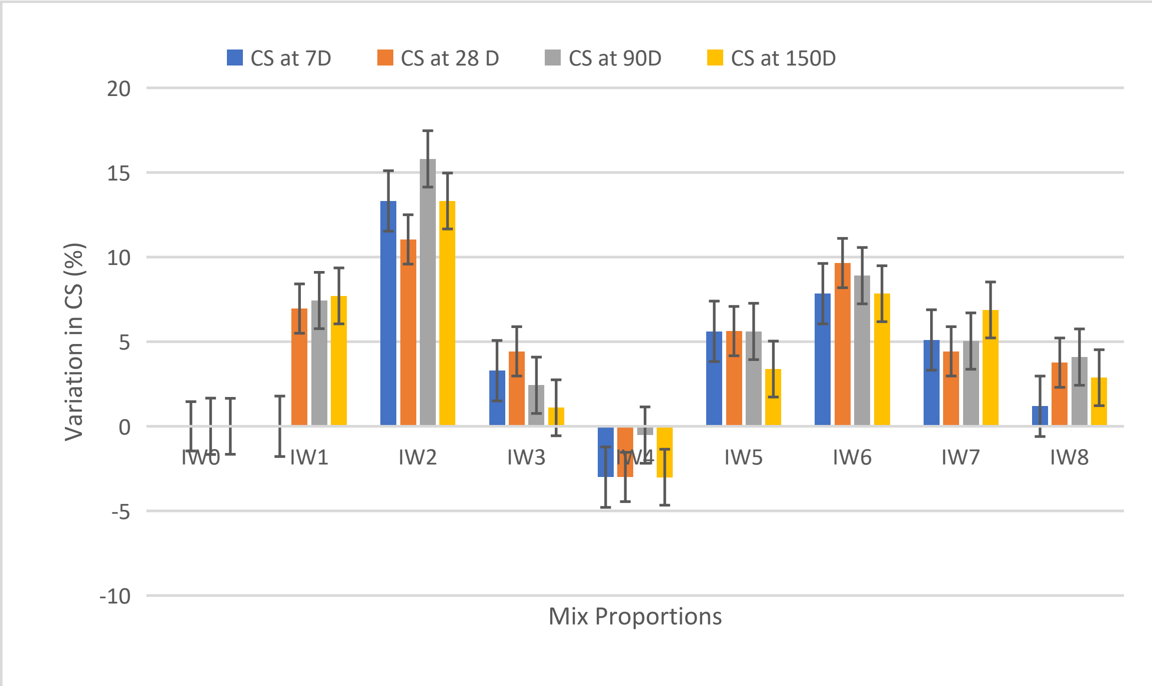

Figure 8. Percentage Change in CS With Reference to the Control Mix.

The variance in the CS of concrete comprising MS and GGBFS, in comparison to the control mix, is illustrated in **Figure 8**. The figure indicates that the greatest increment in strength occurred at 20% GGBFS, with a 11% increase, and at 10% MS, with a 9% increase, relative to the other mixes. The inclusion of GGBFS at 40% diminished the concrete's strength by 3% across all curing durations.

3.2. Rebound Hammer

In **Figure 9**, the values of compressive strength obtained by the rebound hammer test for different concrete mix proportions are shown. The results showed that the compressive strength increased with the addition of industrial waste materials and then decreased slightly at higher replacement levels. This may be due to pozzolanic reactions and improved particle packing, resulting in a denser concrete matrix, which may explain the improvement. The control mix IW0 showed a compressive strength of the order of 35 MPa. For mixes IW1 and IW2, the strength increased; the highest compressive strength was achieved with IW2, with nearly 39 MPa. For IW3 and IW4 mixes, the compressive strength decreased after IW2. The lowest value was observed for IW4, which may be due to excessive cement substitution and reduced cementitious bonding. Again, the mixes IW5, IW6, and IW7 exhibited higher strength values, with IW6 approaching 38 MPa. Error bars on the graph represent the spread in test results of three samples of each mix. In general, the graph shows that using industrial waste materials in optimal proportions improved the compressive strength of concrete.

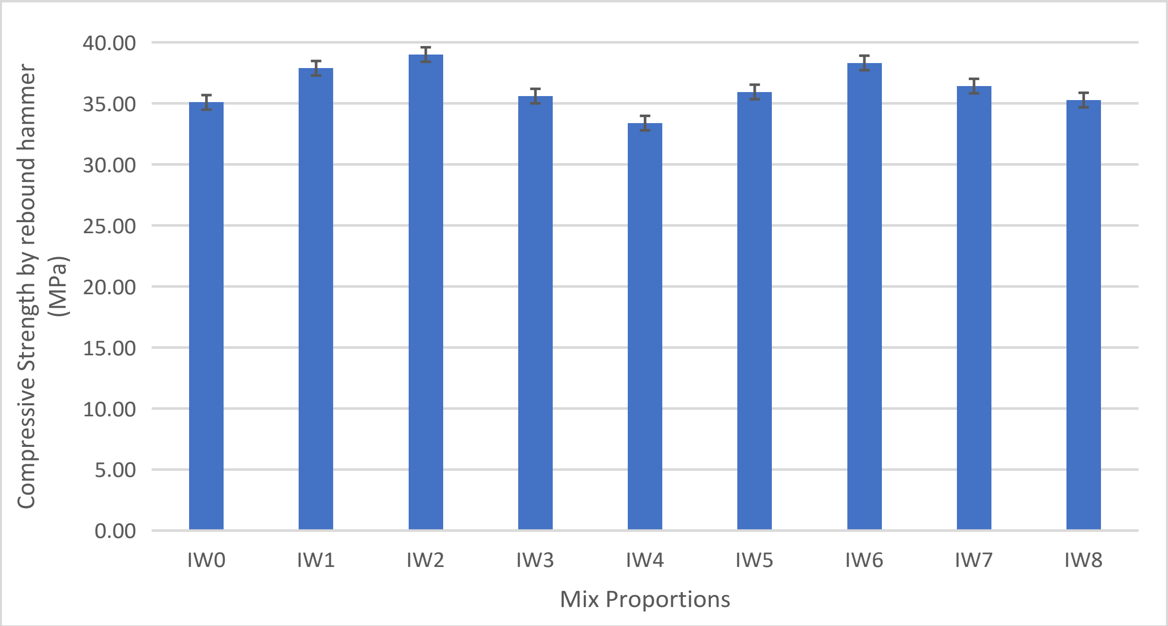

Figure 9. Compressive Strength by Non-Destructive Test of Different Concrete Mixtures.

3.3. Dynamic Modulus

The dynamic modulus (DM), determined by ultrasonic pulse velocity, was measured at 28-day water-cured specimens, and the variation in the DM is shown in **Figure 10**. **Figure 10** represents the dynamic modulus values for the different concrete mixes. The dynamic modulus increased with the addition of industrial waste materials up to an optimum level, then decreased slightly at higher replacement levels. The DM ranged from 25.6 GPa to 42.4 GPa across all mix proportions. The control mix IW0 had a dynamic modulus of about 25 GPa. For the mixes IW1, IW2, IW5, and IW6, the values increased, with the highest, nearly 42 GPa, observed for IW2. This enhancement indicates that the concrete is denser and stiffer due to improved bonding and the formation of additional hydration products. The error bars in the graph represent the scatter of the results from three specimens tested for each mix. In general, the results show that using optimal proportions of industrial waste materials improved the stiffness and elastic behavior of concrete.

Figure 10. Dynamic Modulus of the Concrete Mix Proportions.

3.4. Chemical Resistance

The chemical resistance of the concrete containing industrial wastes such as GGBFS and MS was studied experimentally at the different exposure periods i.e., 7, 28, and 62 days after 28 days of water curing, and presented in **Figure 11**. It has been observed from **Figure 11** that the incorporation of industrial wastes improved the chemical resistance of concrete at the various exposure periods.

The increase in strength may be due to the pozzolanic reaction of GGBFS and MS. The optimum content of GGBFS and MS is 20% and 10% in the concrete against sulphate exposure [33–36]. The maximum increases in strength were 10% for GGBFS and 8% for MS across all exposure periods, as shown in **Figure 11**.

Figure 11. Variation of Compressive Strength of Concrete.

3.5. Carbon Emissions

The carbon emissions and cost of the concrete with the different mix proportions using industrial by-products such as GGBFS and MS were evaluated and given in **Table 8**. The incorporation of industrial by-products into concrete reduces carbon emissions and costs. The carbon emissions and costs of the control mix were the highest among the mixes. From the results, it can be seen that the control mix IW0 had the highest carbon emission value of 368.485 and the highest total cost of INR 5,530. As the percentage of industrial waste materials in the concrete mixes increased, the total carbon emissions gradually decreased. The minimum carbon emission value of 237.745 was observed for mix IW4, indicating that the use of industrial waste materials reduced the environmental impact of concrete. Similarly, the ECO_2/28 days values also decreased from 11.028 for IW0 to 7.336 for IW4, showing better environmental efficiency of the modified mixes. In terms of cost analysis, the total cost decreased from INR 5,530 for IW0 to INR 5,076 for IW4 because partially replacing cement with industrial waste materials reduced material costs. However, mixes IW5 to IW8 showed slightly higher values due to variation in the proportions of materials used.

Table 8. Cost and Carbon Emission of the Different Mix Proportions.

Mix No.	Total Carbon Emissions	ECO_2/28 Days	Total Cost	Cost/28 Days
IW0	368.485	11.028	5,530	166
IW1	335.335	9.384	5,413	151
IW2	302.185	7.981	5,296	140
IW3	269.035	7.860	5,179	151
IW4	237.745	7.336	5,076	157

Table 8. *Cont.*

Mix No.	Total Carbon Emissions	ECO_2/28 Days	Total Cost	Cost/28 Days
IW5	350.74	9.939	5,530	157
IW6	332.995	9.241	5,530	153
IW7	315.25	8.977	5,530	157
IW8	297.505	8.582	5,530	160

Overall, the results indicate that incorporating industrial waste materials into Light Transmitting Concrete can reduce both carbon emissions and overall costs while maintaining satisfactory performance.

3.6. Performance Index

The performance index of the different concrete mixes was evaluated and given in **Table 9**. The performance evaluation encompasses structural characteristics such as 28-day compressive strength, rebound hammer hardness, and dynamic modulus, as well as sustainability indicators, including embodied carbon dioxide emissions and overall material cost.

The findings indicate that integrating industrial waste improved performance and reduced environmental impact. The value 1 is the reference value; higher values indicate superior performance, and lower values indicate inferior performance compared to the reference mix. The IW2 mix demonstrates significant potential, with 10% higher compressive strength, a 60% increase in dynamic modulus, and reductions of 18% in carbon emissions and 4% in costs. IW4 exhibits the minimal environmental footprint, achieving a 35% reduction in CO_2 emissions and 8% cost savings, albeit with a marginal decrease in stiffness, presenting a commendable sustainability-oriented option.

Table 9. Performance Index of Different Concrete Mixtures.

Mix No.	Performance Index				
	CS at 28 Days	CS by Rebound Hammer	Dynamic Modulus (GPa)	ECO_2	Total Cost
IW0	1.00	1.00	1.00	1.00	1.00
IW1	1.07	1.08	1.23	0.91	0.98
IW2	1.13	1.11	1.63	0.82	0.96
IW3	1.02	1.01	1.06	0.73	0.94
IW4	0.97	0.95	0.95	0.65	0.92
IW5	1.06	1.00	1.17	0.95	1.00
IW6	1.08	1.01	1.30	0.90	1.00
IW7	1.05	0.98	1.11	0.86	1.00
IW8	1.04	0.97	1.09	0.81	1.00

3.7. Industrial Waste in LTC

Based on the above experimental results, GGBFS (20%) and MS (10%) were selected as the optimum mix proportions in terms of mechanical strength. The optical fibre at 1% was observed as the optimum content in terms of strength and light transmittance [25]. Therefore, GGBFS (20%) and MS (10%) were used individually in the LTC to evaluate the performance of concrete specimens. The performance of concrete mixes was evaluated in terms of strength and durability.

3.7.1. Compressive Strength of Optimized Mixes

After considering the results presented above, waste products from industrial processes, such as GGBFS (20%) and micro silica (10%), were selected for future investigation. In addition, the LTC used 1% plastic optical fiber in the present work. In the optimized mixes, industrial waste and optical fiber are used. The compressive strength of the optimal mix proportions was measured at three different curing ages, i.e., 7, 28, and 90 days, and the variance in strength was depicted in **Figure 12**. The addition of industrial wastes such as GGBFS and micro-silica increased the compressive strength of the optimum mix proportions throughout the entire curing process, as shown in **Figure 12**. The strength of GGBFS and MS obtained from industrial waste was significantly higher than that of the control mix [34–37]. This was the case when the control mix was used as a comparison. It has been suggested that the development of higher strength may be attributed to the pozzolanic reaction of industrial by-products, as well as the pore-filling effect of their finer particles, as observed in the microstructural analysis [32,34–37]. As can be observed in **Figure 10**, the addition of GGBFS and MS led to an increase in the compressive strength of LTC by 20% and 16% after 28 days of water curing for conventional concrete, and by 5% and 2%, respectively, compared to light-transmitting concrete. This was the case for both types of concrete.

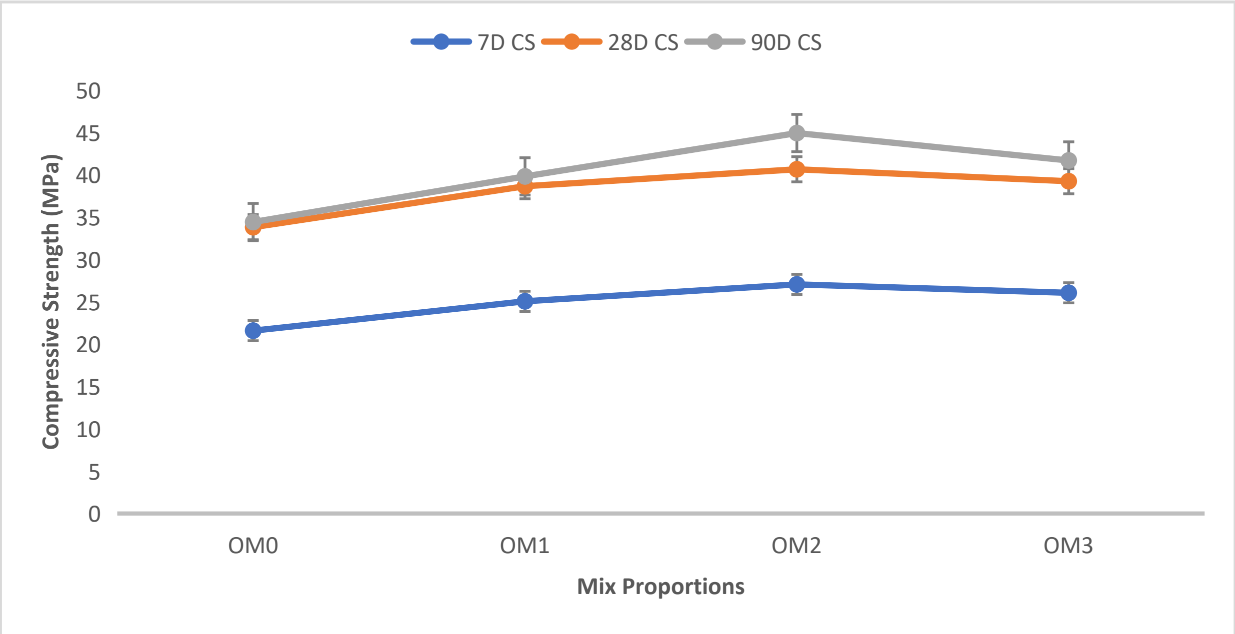

Figure 12. Variation of Compressive Strength of Optimized Mixes of LTC.

3.7.2. Chemical Resistance of Optimized Mixes

The chemical resistance of concrete incorporating optical fiber and industrial wastes, i.e., GGBFS and MS, was experimentally examined at 7, 28, and 62 days. The concrete specimens were exposed to a magnesium sulfate solution, and a fluctuation in strength is illustrated in **Figure 13**. The inclusion of industrial wastes has been found to improve chemical resistance owing to their pore-filling impact and pozzolanic reactions across all exposure durations. The hydration product generated during the pozzolanic reaction compacted the matrix and limited the ingress of external agents into the concrete matrix [34,37]. The industrial waste GGBFS was found to be more effective than MS at enhancing the chemical resistance of LTC. Nonetheless, the concrete, including optical fiber, exhibited enhanced chemical resistance in the mixtures, likely attributable to denser matrix packing compared with the control mix, which contained optical fiber.

The percentage variation in the compressive strength of LTC against exposure to a sulphate solution at exposure periods of 7, 28, and 62 days has been illustrated in **Figure 13**. The maximum increase in resistance was observed for the OM2 mix at 23%, 30%, and 50% compared to the control mix at exposure times of 7, 28, and 62 days, respectively.

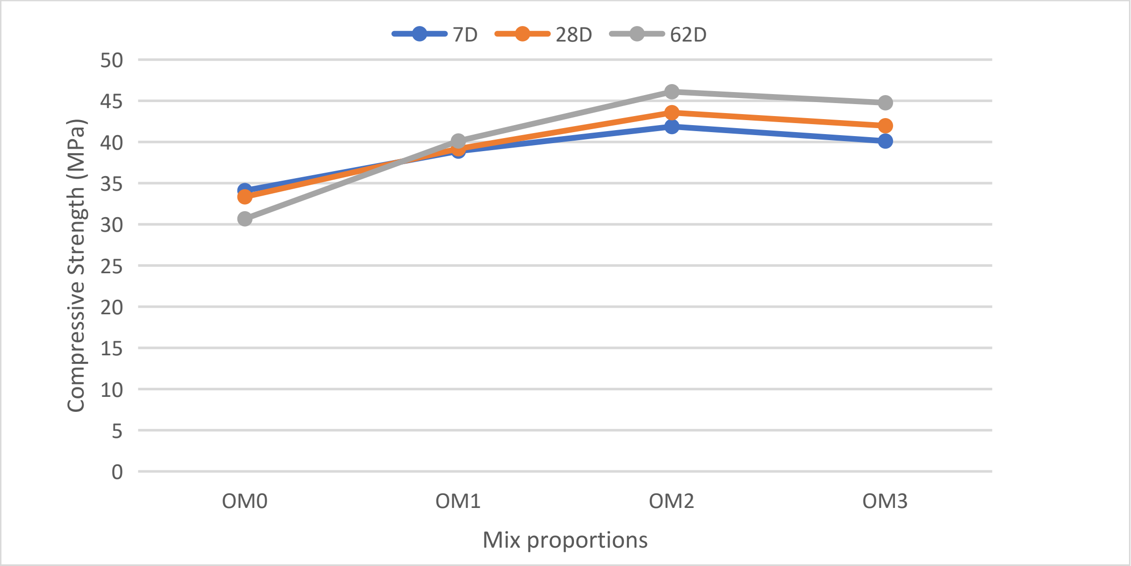

Figure 13. Variation of Compressive Strength Against Chemical Attack.

3.7.3. Cost and Carbon Emission Analysis of Optimized Mix

The cost analysis of the optimized mix proportions was carried out and is shown in **Figure 14**. It is observed from **Figure 14** that the addition of optical fiber increased the cost of concrete; whereas the industrial wastes, i.e., GGBFS, and MS, as cement substitution, marginally reduced the cost. The cost of mixes varied from INR 5,411 to INR 144,988. The GGBFS reduced the cost, and MS had an insignificant effect on the cost of the light-transmitting concrete.

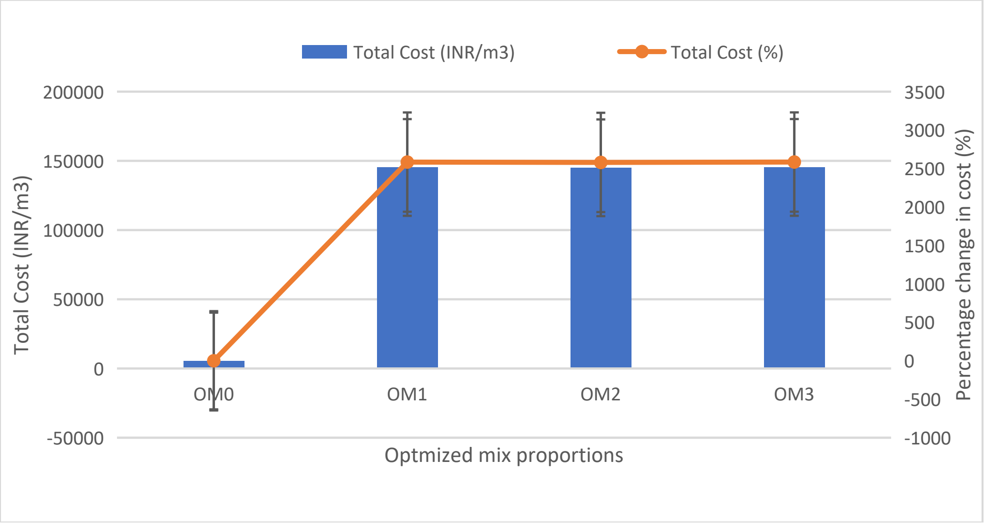

Figure 14. Cost of Optimized Mixes.

Figure 15 shows the carbon emissions of different optimized concrete mixes, namely OM0, OM1, OM2, and OM3. Among all the mixes, OM1 had the highest carbon emissions, at about 441 kg CO_2, which was almost 20% higher than those of the control mix, OM0. This rise can be attributed to the increased use of higher-carbon-footprint materials. On the other hand, OM2 showed carbon emissions very close to the control mix, with a marginal increase of about 2–3%, indicating it is comparatively more eco-friendly and sustainable. The OM3 mixture also showed a moderate increase in carbon emissions, about 10–11% higher than OM0. In general, the results indicate that appropriate optimization of industrial waste materials and additives can help reduce the environmental impact of concrete production while maintaining desired performance characteristics.

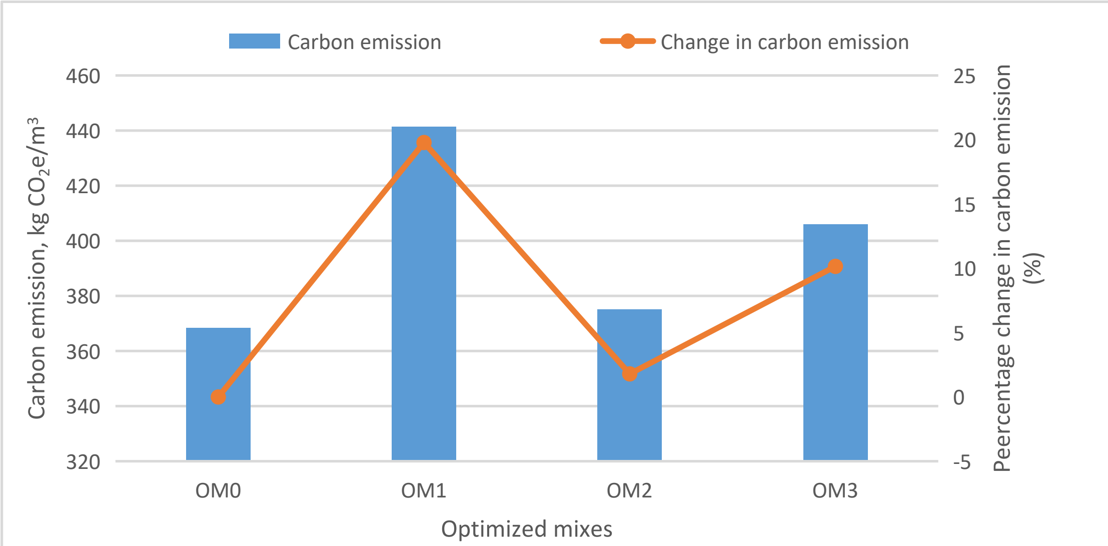

Figure 15. Carbon Emissions of Optimized Mixes.

3.8. Microstructural Analysis and Material Characterization

The microstructural analysis of concrete provides essential insights into material behavior, interfacial properties, and performance mechanisms. Systematic characterization using analytical techniques provides valuable insights into opportunities for improvement and performance prediction. The scanning electron microscopy (SEM) analysis provides clear visuals of microstructural features, interfacial zones, and hydration product formation in concrete specimens. A thorough examination shows key traits that influence performance and durability. The microstructural characterization of concrete with optimized mix proportions has been studied through the SEM technique and is shown in **Figure 16**.

The SEM examination of optical fibre surfaces shows smooth, non-porous features that limit mechanical interlocking with cement paste, as shown in **Figure 16b**. This finding supports the experimental results about bond strength limitations and suggests possibilities for improving surface treatments. The interfacial transition zone (ITZ) between optical fibres and cement paste has characteristics that differ from usual aggregate-paste interfaces. The ITZ's width and porosity seem greater than those in natural aggregate systems, which may lead to lower bond strength and changes in mechanical behaviour. The formation of hydration products around optical fibers exhibits typical cement hydration characteristics but also includes changes attributable to the fiber surface and local chemistry. The microstructural examination of optimized systems incorporating supplementary cementitious materials reveals enhanced matrix characteristics, including refined pore structures, increased hydration product density, and improved interfacial characteristics compared to the control mix, as shown in **Figure 16c**,**d**. The same results were verified experimentally.

The microstructural examination of optimized systems incorporating supplementary cementitious materials reveals enhanced matrix characteristics, including refined pore structures, increased hydration product density, and improved interfacial characteristics compared to the control mix, as shown in **Figure 16a**,**c**,**d**.

Figure 16 shows the SEM images of the different concrete mixes used in the study. **Figure 16a** represents the control mix, where a comparatively porous and less compact structure can be observed. **Figure 16b** shows the optimized Light Transmitting Concrete (LTC) mix containing 1% optical fibre. The matrix appears denser and more uniform, which has helped improve the overall compressive strength and durability of the concrete. **Figure 16c** presents the optimized mix with GGBFS, in which additional hydration products and improved particle packing are observed. The denser microstructure reduced the pore spaces and improved the resistance against sulphate attack, which resulted in better durability and higher compressive strength. Similarly, **Figure 16d** shows the optimized mix containing Micro Silica (MS), which developed a highly compact and refined matrix due to the pozzolanic reaction and the formation of additional C-S-H gel. This improved bonding within the concrete matrix contributed to enhanced strength and durability performance.

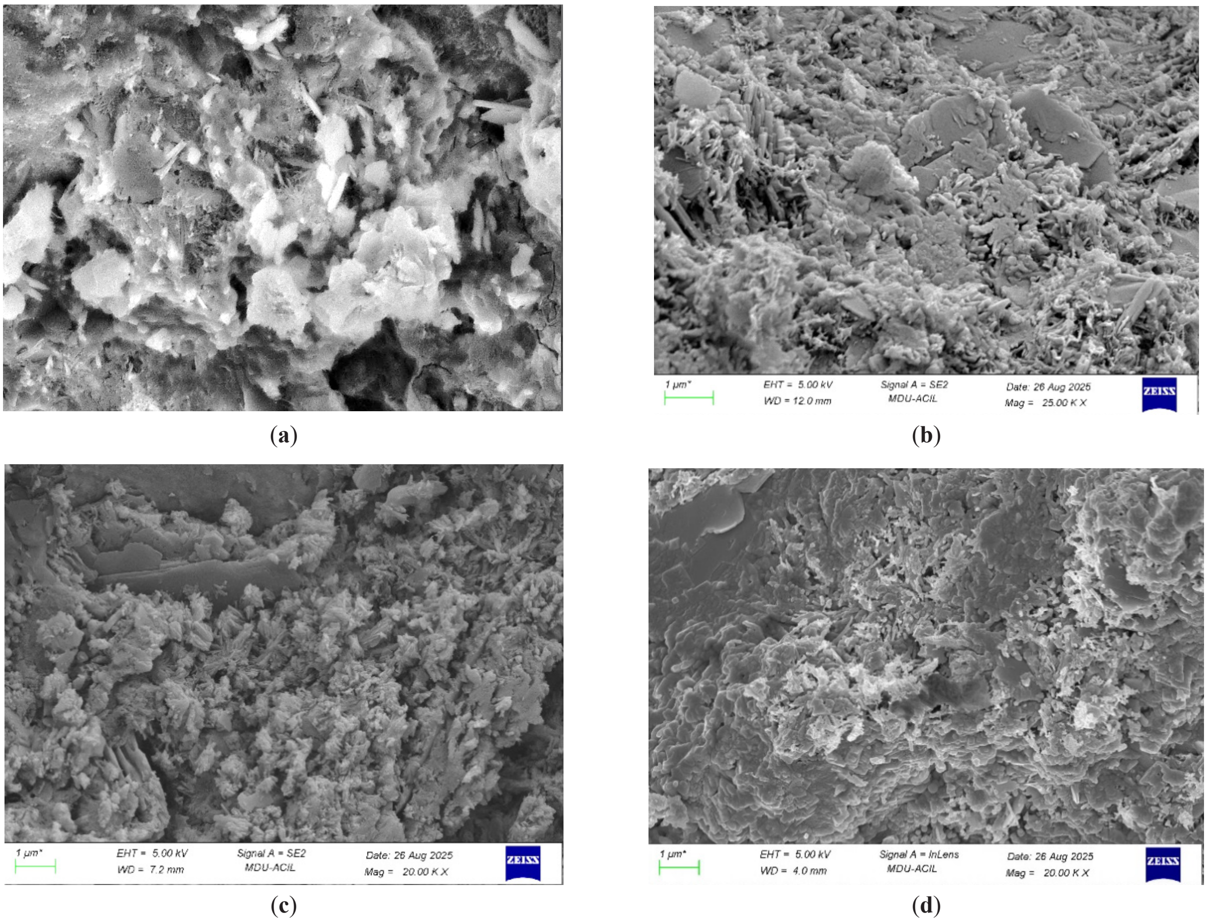

Figure 16. SEM Images of (**a**) Control Mix; (**b**) Optimized Mix of LTC (1% Optical Fibre); (**c**) Optimized Mix with GGBFS; (**d**) Optimized Mix with MS.

Overall, the SEM analysis supports the experimental results of the study, as the mixes with denser, more compact microstructures exhibited greater mechanical strength and durability. The microstructural analysis provides important insights for optimizing the LTC system and enhancing its performance. The fibre surface modification opportunities identified through microstructural analysis suggest potential strategies for improving bond strength and mechanical performance. Surface treatments, coupling agents, or coating systems may provide enhanced interfacial characteristics. The optimized matrix composition strategies revealed through supplementary cementitious material analysis demonstrate practical approaches for enhancing overall system performance. The microstructural improvements support both mechanical and durability enhancements. The quality control implications of microstructural analysis include identifying critical features that affect performance and developing evaluation procedures to ensure consistent quality. The microstructural understanding supports practical quality assurance procedures.

4. Conclusions

In the present study, the influence of industrial wastes, i.e., GGBFS and MS, at different percentages in various concrete mixtures on strength, cost, and carbon emissions was studied experimentally. It was observed that the addition of industrial by-products such as GGBFS and MS up to a certain percentage, 20% and 10%, respectively, enhanced the CS of the concrete by 13% and 7%, respectively, which may be due to pore-filling effects of the finer particles of both the additives, resulting in densification of the matrix, consequently, strength improved for the concrete specimens. The strength determined by both destructive and non-destructive techniques followed the same trend. Also, the elastic modulus of the different concrete mixtures was improved with the incorporation of industrial by-products. The optimal contents of strength and dynamic modulus were 20% and 10% for GGBFS and MS, respectively. However, the incorporation of GGBFS and MS has reduced concrete production costs and carbon emissions. The mix IW4 had the lowest values for cost and carbon emissions. It was concluded that the use of GGBFS at 20% and MS at 10% had the optimum results in all the desired parameters. The use of industrial by-products in concrete improved the performance of the concrete mixtures and reduced costs and environmental impacts. The performance index for GGBFS at 20% and MS at 10% was superior to that of the other mixes.

In the case of light-transmitting concrete, the optimal content of optical fiber (1%) and industrial waste improved its performance. The improvement in performance in terms of strength, chemical resistance, and cost may be due to the presence of finer particles that fill the voids and pozzolanic reaction, resulting in the formation of a dense matrix. The same has been justified by the microstructural analysis of different mixes. Therefore, the incorporation of an optimum content of GGBFS and MS along with the addition of plastic optical fibre improved the performance of the light-transmitting concrete.

Author Contributions

Conceptualization, K.S. and K.D.; methodology, K.S. and K.D.; validation, K.D.; resources, K.S.; data curation, K.S.; writing—original draft preparation, K.S.; writing—review and editing, K.D. and N.S.; supervision, K.D. and N.S.; project administration, K.D. and N.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. The research was conducted in the absence of any financial relationships that could be construed as a potential conflict of interest.

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