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Evaluation of performance-based characteristics in high-performance concrete modified with ferro slag aggregates and admixtures

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ABSTRACT

Newly developed high-performance concrete (HPC) is a revolutionary building material with superior mechanical properties and enhanced durability. Researchers have optimized HPC by incorporating industrial byproducts like modified ferro slag, silica fume, and fly ash, promoting sustainability and reducing carbon emissions. This paper analyzes the mechanical characteristics of HPC using the American Concrete Institute (ACI-211.1-91) guidelines, substituting cement with 17% fly ash (FA) and 10% silica fume (SF), and replacing coarse aggregate with up to 40% modified ferro slag. M60 grade was adopted for all mixes. Experimental tests assessed compressive strength (CS), split tensile strength (STS), and flexural strength (FS). Results showed significant improvements, with CS surpassing conventional HPC mixes by up to 25%. The highest CS, STS, and FS were observed with 30% modified ferro slag, achieving 10%, 6%, and 9% increases, respectively, at 28 days. These improvements indicate enhanced structural integrity and resistance to cracking. Utilizing industrial byproducts in HPC not only boosts performance but also supports sustainable construction by reducing waste and conserving natural resources.

Keywords: High performance concrete; Silica fumes; Flyash; Ferro slag; Compressive strength; Split tensile strength; Flexural strength; Modulus of elasticity.

1. INTRODUCTION

Concrete containing ferro slag as a substitution for coarse aggregate offers an eco-friendly and sustainable substitute to conventional concrete. It provides an opportunity to expand the properties of concrete while contributing to the decrease of industrial waste and its environmental impact. Proper research, testing, and mix design optimization are essential for successfully implementing this innovative concrete material in construction projects. For w/c ratios extending from 0.26 to 0.42, the workability of the concrete attenuations with a large percentage increase in silica fume content from 0% to 25%. The properties increase with rise in silica fume incorporation [1]. As the proportion of Coal Gasification Coarse Slag (CGCS), also known as copper slag, in the mixture increased, a concurrent reduction was observed in the water-binder ratio (w/b), FS, and CS. Samples containing CGCS at levels up to or below 25% exhibited the capacity to fulfill the strength requirements for non-structural UHPC. These samples achieved a FS of 29 MPa and a CS of 111 MPa on the 28th day [2]. By adding 10% ground-granulated blast furnace slag (GGBFS) to HPC, the compressive strength can be increased by 37% [3]. In the realm of HPC, the most employed pozzolanic materials include substances like fly ash and silica fume. However, it is worth noting that there are instances in HPC and UHPC where blast furnace slag is also utilized. Silica fume stands out as a particularly favorable pozzolan due to its exceptional characteristics, including a substantial specific surface area, a significant amorphous composition, and a substantial SiO2 content exceeding 95% [4]. When silica fume, bottom ash, and steel slag aggregate were used in combination, it enhanced the mechanical properties of HPC. Consequently, these three materials can be considered as suitable candidates for partial replacement in the production of HPC [5]. Incorporating 10% silica fume into the cement component resulted in the formation of a more robust and compact interfacial transition zone (ITZ) between the coarse particles of concrete and the cement matrix [6]. The results of the experiment showed that the highest compressive strength, reaching around 99 MPa, was achieved by High-Performance Concrete (HPC), which is

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made up of 1.2% steel fibres, 10% silica fume, and a w/c ratio of 0.25. Conversely, HPC containing 15% silica fume displayed the highest STS at 7.4 MPa and FS at 14.6 Mpa [7]. The mechanical properties were enhanced with the incorporation of nano-TiO2. The mixture containing 20% FA with 1.2% nano-TiO2 attained the highest CS of 208.9 N/mm^2 after 28 days [8]. The inclusion of 10% silica fume led to a 26% enhancement in tensile splitting strength, a 13% improvement in compression strength, and 5% rise in the static modulus of elasticity. The presence of SF was found to amplify the brittleness of High-Performance Concrete [9]. Based on the mechanical property outcomes, an optimal silica fume content of 15% was identified. Concrete with 15% silica fume exhibited an average shrinkage increase from 0.051% to 0.085% at 28 days [10]. Furthermore, combining 15% Waste Glass Powder (WGP) and 15% GGBFS in binary mixtures resulted in a 45% reduction in water penetration depth. SEM microstructure analysis revealed that the inclusion of SF, along with WGP and GGBFS, enhances packing density. Ultimately, the addition of 5% SF is recommended for enhancing the properties of concrete mixtures containing WGP and GGBFS [11]. It is noted that the blend comprising 50% FA and 50% bottom ash as fine aggregate exhibits nearly equivalent compressive strength, a 10% increase in STS, and higher FS compared to the standard concrete. However, it also displays a 12.15% lower density than the control concrete [12]. The compressive strengths of ferrochrome slag concretes surpass conventional concrete by 15.8% and 3.6%, respectively. Moreover, the water absorption of low-carbon concrete incorporating ferrochrome slag is superior to that of traditional concrete [13]. Ferro slag aggregate exhibits physical and mechanical characteristics that outperform various natural aggregates, including limestone. Employing ferro slag as a coarse aggregate, up to 100%, enhances concrete's mechanical properties [14]. Augmenting the quantity of steel slag in concrete resulted in a reduction of its compressive strength, especially in terms of early strength, permeability, and resistance to carbonation under consistent water-to-binder conditions. Nevertheless, at lower water-to-binder ratios, the detrimental impacts of steel slag on compression strength, permeability, and carbonation resistance in concrete were less evident [15]. Concrete beams incorporating steel slag exhibited commendable ductility characteristics, especially with a tension reinforcement ratio of up to 3.6% [16]. The maximum crack width, total number of cracks, and average fracture spacing in both UHPC beams were significantly influenced by the specimen size. On the other hand, neither Ultra High-Performance Concrete beam's ductility was significantly affected by size [17]. The flexural strength of HPC beams, subjected to curing at 20 °C, demonstrated enhancement with an escalation in the reinforcement ratio. When the reinforcement ratio rose from 1.26% to 9.5%, the failure modes of HPC beams changed from ductile to brittle [18]. The HPC's high compressive strength and deformation capacity enable the utilization of elevated reinforcement ratios in beams. This leads to more cost-effective sizes, provided that the beam deflections satisfy both serviceability and ultimate limit states [19].

Elevating the percentage of longitudinal tension steel in beams of the same HPC grade resulted in an augmentation of the load associated with the first visible crack. The failure in these beams occurred in the tension zone, accounting for an average of 76.70% of the ultimate load [20]. Incorporating palm oil fuel ash (POFA) POFA into concrete mixes at dosages up to 12% enhances compressive, flexural, and splitting tensile strengths. However, higher POFA content reduces workability [21]. Adding Nano Silica (NS) to concrete can significantly enhance its mechanical properties and resistance to chloride penetration. The optimal NS substitution amount is two to three percent. However, if the NS proportion is too high, the benefits of incorporating NS into the concrete properties diminish [22]. In the current study, HPC, specifically modified ferro slag aggregate concrete, was manufactured following the American Concrete Institute (ACI-211.1-91) standards. This required adding SF and FA to the regular concrete mixture. Additionally, ferro slag aggregate was used in diverse amounts (ranging from 0% to 100%) to partially replace the traditional natural coarse aggregate. Fly ash and silica fume were introduced as partial replacements for cement. A uniform M60 grade was employed for all concrete mixes. Specimens were prepared for both normal concrete mix (MF0) and modified ferro slag aggregate concrete mixes (MF20, MF30, and MF40). These specimens underwent experimental tests to assess mechanical properties such as CS, STS and FS. Furthermore, beam specimens were crafted using reinforced normal concrete mix and modified ferro slag concrete mix. These beams were then tested to evaluate their flexural strength and to analyze the load versus deflection behavior under a simply supported condition.

2. MATERIALS AND METHODS

2.1. Cement, flyash and silica fumes

53-grade Ordinary Portland Cement (OPC) that complied with IS 12269, 1987 [23] was purchased from the neighbourhood market and used to create a variety of concrete mixtures. It was found that the cement's initial setting time was 35 minutes, and its specific gravity was 3.18. The Thermal Power Station in Chennai provided Class F flyash which was used in part place of cement. Table 1 provides a thorough list of the fly ash's chemical characteristics. Furthermore, during the study, dark grey silica fumes with a specific gravity of 2.3 were used; Table 2 lists their characteristics.

Table 1: Chemical composition of cement and fly ash used in the study.

COMPOSITION/ PROPERTIES	CEMENT (%)	FLY ASH CLASS F (%)
SiO_2	20.81	59.3
Al_2O_3	4.79	34.6
Fe_2O_3	3.2	5.87
CaO	63.9	1.02
MgO	2.61	0.38
SO_3	1.39	0.1
Na_2O	0.18	1.28
K_2O	0.79	0.01
Cl^-	0.002	0.49
Loss on ignition	0.98	1.9
Insoluble residue	0.12	–
Moisture content	–	0.73
Specific gravity	3.17	2.24

Table 2: Properties of silica fume.

SL. NO.	DESCRIPTION	VALUES
1	Specific gravity	2.1
2	Specific surface area	8340 m^2/kg
3	Mean grain size	0.15 µm

Table 3: Properties of natural coarse aggregate.

SL. NO.	DESCRIPTION	COARSE AGGREGATE	FERRO SLAG
1	Specific gravity	2.76	2.82
2	Bulk density	1653.06 kg/m^3	1613.06 kg/m^3
3	Surface moisture	0.086%	0.05%
4	Water absorption	1.00%	0.8%
5	Fineness modulus	6.98	7.2
6	Impact value	25.3%	26.5%
7	Crushing value	25.5%	27.5%
8	Abrasion value	26.5%	28.1%

2.2. Fine aggregate and coarse aggregate

For the investigation, locally produced river sand was used as fine aggregate. This sand complied with IS 383, 1970's Grading Zone-II requirements and was able to pass through a 4.75 mm IS sieve [24]. The sand used in the concrete mixtures for this investigation met the previously stated requirements and was free of silt and clay. For the coarse aggregate, ferro slag aggregate made from steel waste and blue granite stone were used. For every concrete mix, the coarse aggregate size was standardised at 12.5 mm. The natural stone aggregates had specific gravity, fineness modulus, and water absorption values of 2.75, 7.20, and 0.62%, respectively, and were chosen in compliance with IS 383, 1970 [24]. Another coarse aggregate used in the research study was ferro slag aggregate, which comes from the steel industry. The chosen aggregates were sieved, and the parts that were collected on a 10 mm sieve and went through a 12.5 mm sieve were used in the mix [25, 26]. Ferro slag aggregate was found to have a fineness modulus of 7.2 and a specific gravity of 2.82. Table 3 lists the specific characteristics of both ferro slag and natural aggregate.

2.3. Chemical admixture

Fly ash was subjected to a high-range water reducer chemical admixture, CONPLAST SP 430, in order to speed up the pozzolanic reaction. The fly ash concrete mixture had a 26% solid content and a specific gravity of 1.81.

A polycarboxylate-based superplasticizer was supplemented to the concrete mixes to improve their workability properties [27]. To produce the acceptable workability within the range of 75 to 100 mm slump for all mix proportions, the superplasticizer dosage was limited to a extreme of 1.5% (by weight of the binder). Table 4 lists the physical characteristics of silica fume.

2.4. Mix proportion

The concrete mix design for achieving M60 grade concrete was formulated in accordance with ACI Standards 211.4R [28], which provides guidelines for choosing proportions for high-strength concrete using Portland cement and other cementitious materials. Two kinds of coarse aggregate - natural granite stone of 12.5 mm size and steel slag of 12.5 mm size were used. The mix proportion adopted for concrete is sown in Table 5.

To reach the desired strength, additives, including FA and SF, were added to the concrete mixture. The percentage of ferro slag aggregate substituted for the natural aggregate was changed, ranging from 0% to 40%. For every blend, estimated superplasticizer was added to the concrete mixture. The design mix was used to determine the mix proportion, which included replacing natural aggregate with ferro slag aggregate. Silica fume was introduced as an admixture in the concrete mix, with a dosage set at 10% of the weight of the cement content. Fly ash was used as partial substitution for cement content and in such a quantity to keep the cement content below 450 kg/m^3 in the concrete. The final design concrete mix proportions were arrived by selecting the most appropriate proportions of the constituents and were presented in the Table 6.

Table 6 presents the modified mix proportions in which coarse aggregates were replaced with ferro slag aggregate in increments of 10%.

Table 4: Properties of silica fume.

SL. NO.	DESCRIPTION	VALUES
1	Specific gravity	2.1
2	Specific surface area	8340 m^2/kg
3	Mean grain size	0.15 µm

Table 5: Mix proportion adopted (M60 grade).

CEMENT BINDER kg/m^3	FLY ASH	SILICA FUME	FINE AGGREGATE	COARSE AGGREGATE	WATER Litre/m^3	SUPER PLASTICIZER Litre/m^3
382.5	76.5	51	716.17	1186.56	143	4.531
MIX RATIO						
1			1.40	2.32	0.28	0.008

Table 6: Concrete mix design proportions.

MIX ID	CEMENT	FLY ASH	SILICA FUME	FINE AGGRE-GATES	COARSE AGGREGATES			
					NATURAL AGGRE-GATES	FERRO SLAG AGGRE-GATES	WATER (L/m^3)	SUPER PLASTI-CIZER (L/m^3)
(kg/m^3)								
MF0	382.5	76.5	51	716.17	1186.56	0.00	143	4.54
MF10	382.5	76.5	51	716.17	1067.90	118.65	143	4.54
MF20	382.5	76.5	51	716.17	949.24	237.31	143	4.54
MF30	382.5	76.5	51	716.17	830.59	355.96	143	4.54
MF40	382.5	76.5	51	716.17	711.93	474.62	143	4.54

3. EXPERIMENTAL INVESTIGATION

3.1. Mechanical properties

The goal of the experimental work was to examine the and mechanical properties of modified ferro slag aggregate concrete in high performance concrete for various mix types. To find the concrete's CS, standard-sized concrete cube specimens of 10 cm by 10 cm by 10 cm were cast and tested. The surface of the cube was made even so as to support the loading equally on the face of the concrete cube. The concrete specimens after having been cured in water were air dried for one hour at room temperature. Following three, seven, and twenty-eight days and 56 days of cure, the concrete cube specimens were evaluated [29]. Concrete cylinder specimens with conventional dimensions of 15 cm by 30 cm were cast and tested to find the concrete's indirect tensile strength. For all of the concrete samples, the testing was done with a digital compression machine with a 1000 kN capacity and a 2 kN/sec rate. The concrete samples were allowed to air dry for an hour at room temperature after the proper water curing period. The testing protocol outlined in the IS5816, 1985 [30] Code was adhered to. To find the concrete's flexural strength, 50 cm x 10 cm x 10 cm standard size concrete prism beam specimens were made and put through testing. An Universal Testing Machine (UTM) with a 2000 kN loading capability was used to test the specimens. The experiment was conducted using the third point loading setup method specified in Indian Standards - IS 516,1959 [31].

3.2. Flexural behavior of ferro slag Rc beams

The concrete mix was prepared in a rotating drum and running it for two minutes to overcome the segregation of the constituents. Steel moulds were fabricated and their sides were cleaned and oiled. By using modified ferro slag concrete mixes of different proportions, reinforced concrete beam specimens of size 100 cm × 10 cm × 15 cm were cast in the moulds as shown in Figure 1 For each kind of concrete mix (M0,M10 MF20, MF30, and MF40), 5 concrete specimens were produced for testing the FS of the concrete. The slump of the modified matrix mixes was maintained at 75 mm. The beam specimens were provided at the top and bottom with steel rods of 2 pieces of 8 mm diameter and 2 pieces of 12 mm diameter as compression reinforcement and tension reinforcement respectively. During casting, the concrete mix (M60 grade) was compacted by using a needle vibrator to get a non-porous, homogeneous concrete. Excess concrete was removed by flattening the top surface by using a trowel. The concrete beam specimens were detached from the moulds and cured in water for 28 days in a curing tank. The concrete specimens were kept in room temperature for 12 hours and then exposed to flexural strength test. The reinforced concrete beam specimen was placed on a rigid frame in the manner of simply supported. The supports were placed at either end of the beam. The length between the two supports was made as 850 mm (L). The beam was tested for its flexural strength by using a UTM. Dial gauge was placed at the bottom mid span to measure the mid deflection in the beam. Two-point loading was applied on the top face of the beam on two points lying at a distance of L/3.

4. SCANNING ELECTRON MICROSCOPIC ANALYSIS OF CONCRETE MIXES

Specimens of concrete mixes are studied under a scanning electron microscope (SEM) or by X-ray diffraction method. In SEM analysis, high energy electrons are released to hit on the surface of the object (concrete specimen); the electron-object matter interactions are reflected in the form of signals. These laser signals are received by the microscope and converted into two-dimensional image. In this context, a scanning electron microscope (SEM) image illustrates the spatial variance in the object's material characteristics. It is possible decipher from SEM image the external morphology, internal structure, disposition of major planes and axes of crystals, and the chemical composition of the object (concrete specimen). SEM analysis is widely practised in civil engineering

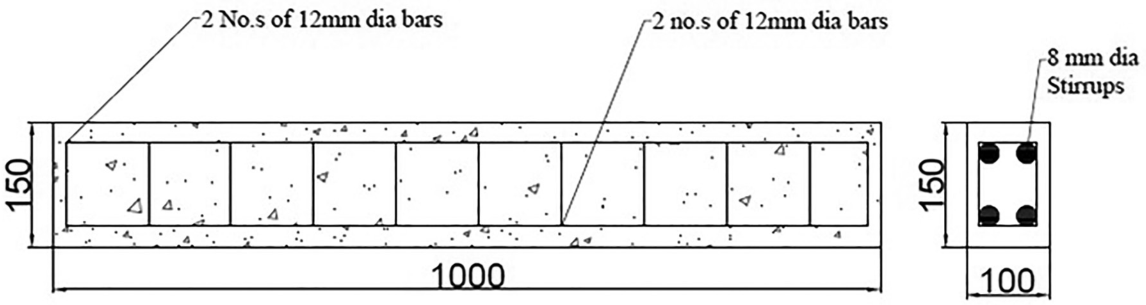

Figure 1: RC beam reinforcement.

field to study the soundness of concrete. It is possible to image objects having a width of about 1 cm to 5 microns using a SEM in its scanning mode. A SEM's magnification power ranges from 20× to 30,000×. It can produce high resolution images with a spatial resolution of 50 to 100 nm. Thus using SEM we can examine concrete specimens and evaluate the quality of the materials used in the concrete mix.

5. RESULTS AND DISCUSSION

5.1. Compressive strength

Based on test results, the CS of concrete mix MF30 was enhanced by partially substituting ferro slag aggregate for natural coarse aggregate. A 30% replacement of ferro slag was found to have a better compressive strength than the other proportions, and the strength of the concrete dropped as the proportion of ferro slag replacement rises beyond 30%. The maximum compressive strength of 71.22 Mpa and 72.1 Mpa was obtained at 28 days and 56 days of curing was achieved for MF30 which is 10% and 11% respectively higher than MF0. Silica fume (SF) enhances the density and compressive strength of concrete primarily through its pore-filling action. As an ultra-fine pozzolanic material, silica fume particles are about 100 times smaller than cement particles, allowing them to fill the microscopic voids and capillary pores within the cement matrix. This results in a denser, less porous concrete structure. The reduction in porosity not only minimizes the ingress of water and other harmful substances but also contributes to a stronger matrix. Additionally, the high reactivity of silica fume leads to a pozzolanic reaction with calcium hydroxide, a by-product of cement hydration, forming additional calcium silicate hydrate (C-S-H) gel. This secondary C-S-H gel further densifies the concrete and increases its compressive strength, making the overall structure more robust and durable [32].

The bonding of the ferro slag surface texture and the hydration of cement with the ferro aggregate improved the concrete's CS to a greater degree. The density and CS of the concrete were both raised by the addition of SF to the mixture. The growth of concrete strength can be attributed to the pore-filling action of tiny silica fume particles. A partial cement alternative was used: fly ash. When combined with cement, it enhanced the cementitious properties of the constituents of concrete. SF plays a crucial role in enhancing the density and compressive strength of concrete through its pore-filling action. By filling the microscopic voids within the concrete matrix, SF reduces porosity and creates a denser, more cohesive structure. This densification leads to significant improvements in the compressive strength of the concrete, making it more durable and resilient [33]. The experimental results are displayed in Figure 2 as a bar chart and in Table 7.

5.2. Split tensile strength

The tensile strength test results for the reference and modified ferro slag concrete mixes are shown in Table 8. All of the concrete mixtures that included ferro slag aggregate were found to have greater tensile strength values than the standard mix (MF0). To be more precise, mix MF30's concrete outperformed other mixes in terms of tensile strength due to the 30% substitution of ferro slag aggregate for natural aggregate. The split tensile strength of 3.21 Mpa and 3.5 Mpa was obtained at 28 days and 56 days of curing for MF30, which is 6% and 13% respectively higher than MF0. Fly ash, silica fume (SF), and ferro slag all enhance the density and split tensile strength of concrete through their pore-filling action. Fly ash, with its fine particles, fills the voids and capillary pores within the concrete matrix, leading to a denser and more compact structure. Similarly, silica fume, being an extremely fine pozzolan, not only fills these voids but also reacts with calcium hydroxide to

Table 7: Compressive strength of different concrete mixes.

MIX ID	CEMENT	FLY ASH	SILICA FUME	COARSE AGGREGATES		3RD DAY (MPa)	7TH DAY (MPa)	28TH DAY (MPa)	56TH DAY (MPa)
				NATURAL AGGREGATES	FERRO SLAG AGGREGATES				
	(kg/m³)								
MF0	382.5	76.5	51	1186.5	0	40.47	51.42	64.25	65.1
MF20	382.5	76.5	51	949.24	237.51	43.78	55.63	69.52	70.5
MF30	382.5	76.5	51	830.59	355.96	44.41	56.43	71.22	72.1
MF40	382.5	76.5	51	711.94	474.62	44.85	56.96	70.51	70.8

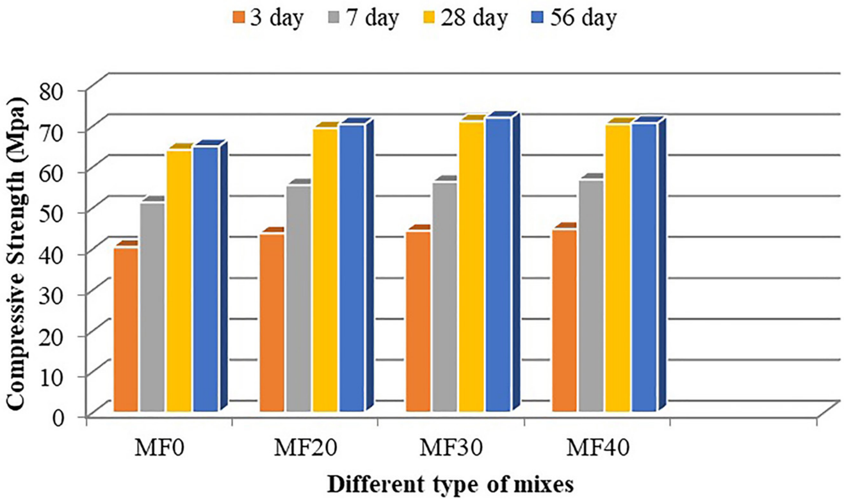

Figure 2: Compressive strength.

Table 8: Split tensile strength of different concrete mixes.

MIX ID	CEMENT	FLY ASH	SILICA FUME	COARSE AGGREGATES		3RD DAY (MPa)	7TH DAY (MPa)	28TH DAY (MPa)	56TH DAY (MPa)
				NATURAL AGGRE-GATES	FERRO SLAG AGGRE-GATES				
	(kg/m³)								
MF0	382.5	76.5	51	1186.5	0	1.22	2.44	3.05	3.1
MF20	382.5	76.5	51	949.24	237.51	1.25	2.51	3.12	3.25
MF30	382.5	76.5	51	830.59	355.96	1.28	2.56	3.21	3.5
MF40	382.5	76.5	51	711.94	474.62	1.20	2.41	3.01	3.1

form additional calcium silicate hydrate (C-S-H) gel, further increasing the concrete's density and cohesiveness. Ferro slag, as an aggregate, contributes to this densification by replacing traditional aggregates and reducing the overall porosity. The combined effect of these materials filling the micro and nano-scale voids results in a denser concrete matrix, which enhances its split tensile strength by improving the bond between the cement paste and aggregates and reducing the presence of weak points where cracks can initiate [22, 32].

Conversely, the strength of mix Tensile strength decreased as the amount of replacement rose, according to MF40. Furthermore, the splitting behaviour of the ferro slag aggregate concrete mix was more than that of the natural aggregate concrete mix. This aspect can be attributed to the strong bonding between the ferro slag and the cementitious compounds [34]. Silica fume enhanced the bonding of the aggregate and cement particle, turned the concrete matrix into a better homogeneous mass, and increased the density of the concrete matrix. It also improved the strength of the concrete with its pore-filling effect. The presence of siliceous material in the silica fume accelerated/kindled the hydration of the cementitious compounds [35]. The adding of FA to the concrete facilitated the hydration of the cement and silica fume [36]. The ferro slag concrete mix showed an overall increase in the STS of the concrete. STS of different concrete mixes was graphically as shown in Figure 3.

5.3. Flexural strength

The results of FS of the concrete of reference and ferro slag modified concrete appear in Table 9. It was found that all the modified mixes bore higher values of flexural strength than that of the conventional mix (MF0). The concrete mix MF30 which substituted 30% of the natural coarse aggregate with ferro slag aggregate, demonstrated a greater flexural strength value in comparison to the other mixes used in the study. Higher flexural strength of 6.4 MPa and 6.70 Mpa was observed for the Mix ID MF30 at 28 days and 56 days respectively. The FS of MF30 is 4% and 9% higher than MF0 at 28 days and 90 days respectively. Fly ash, silica fume (SF), and ferro slag significantly enhance concrete density and flexural strength primarily through their pore-filling action.

These fine-grained materials effectively occupy the voids within the concrete microstructure, reducing porosity and increasing the material's compactness. This denser matrix improves resistance to external forces, leading to higher flexural strength. Additionally, the pozzolanic reactions of fly ash and silica fume contribute to the formation of hydration products that further fill pores and enhance the overall concrete properties [37, 38]. The flexural strength of the concrete of different mixes is illustrated through a bar chart in Figure 4.

5.4. SEM analysis

5.4.1. Scanning Electron Microscopic (SEM) analysis of conventional concrete

In the current research SEM analysis was carried out on samples of conventional concrete mix and ferro slag concrete mix. Besides using standard ingredients like cement, fine aggregate (river sand), natural blue metal coarse aggregate and water, normal concrete mix was equipped with the adding of admixtures – SF and FA - partially replacing cement. SEM images were taken of specimens from the normal concrete mix at magnification levels of 2.5kx, 5kx, 7kx, 25kx, and 50kx.

The steel slag particles are coated in a coating of hydration products, which help the particles bond strongly with the gel round them. The hydration process of steel slag powder causes C-S-H gels to develop, which blurs the distinctive edges of the steel slag particles. Hydration products are generated at the surface of steel slag aggregates, establishing a robust connection with the hardened paste. The pore structure of the hardened paste is notably limited owing to an extremely low water-to-binder ratio. Nonetheless, when the cement replacement ratio rises, the hardened paste's cumulative pore volume—which contains steel slag powder sees a notable increase.

Figure 5 portrays the SEM images of normal concrete mix taken at 25kx and 50kx magnifications. The images reveal that the cement particles within the concrete mix appear as small, grey rectangular pieces adhering

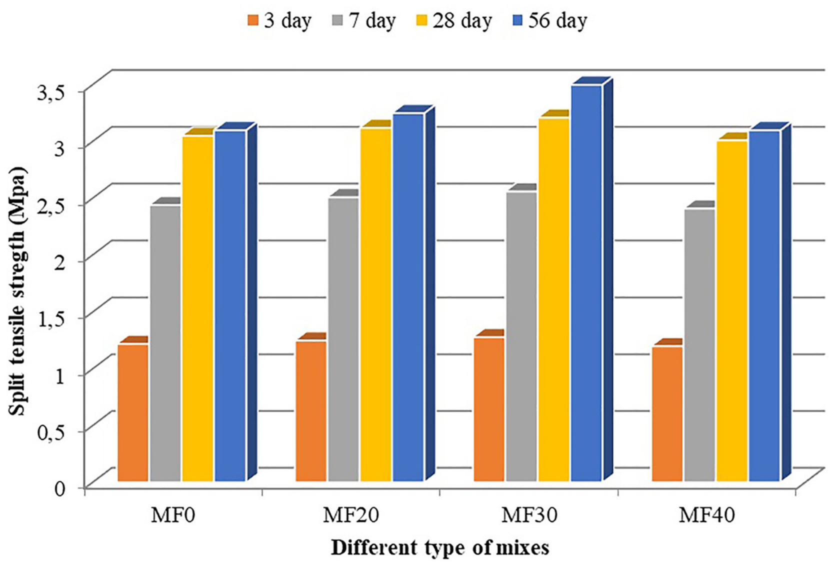

Figure 3: Split tensile strength.

Table 9: Flexural strength of different mixes.

MIX ID	CEMENT	FLY ASH	SILICA FUME	NATURAL AGGREGATES	FERRO SLAG AGGREGATES	3 DAY (MPa)	7 DAY (MPa)	28 DAY (MPa)	56 DAY (MPa)
	(kg/m³)								
MF0	382.5	76.5	51	1186.5	0	2.44	4.88	6.1	6.15
MF20	382.5	76.5	51	949.24	237.51	2.5	5	6.25	6.30
MF30	382.5	76.5	51	830.59	355.96	2.56	5.12	6.4	6.70
MF40	382.5	76.5	51	711.94	474.62	2.412	4.824	6.03	6.12

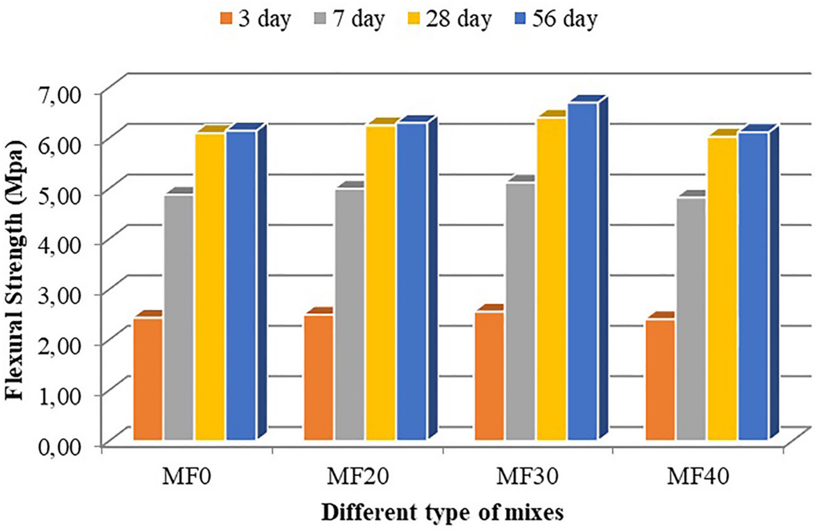

Figure 4: Flexural strength.

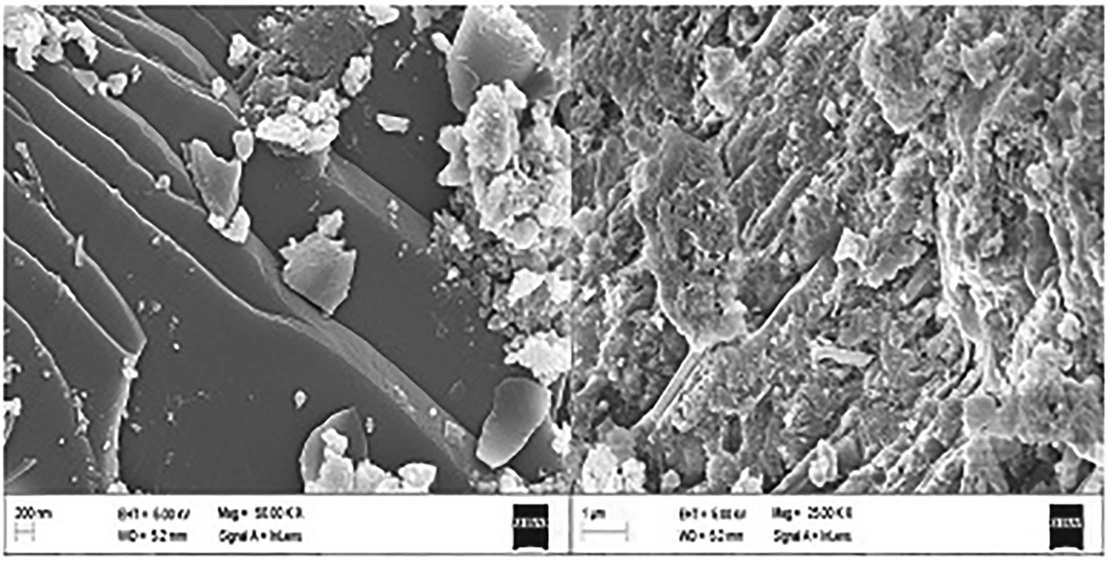

Figure 5: SEM images of conventional concrete at 25kx and 50kx magnifications.

to the silica fume. White swelled elements of silica fumes stay stuck with the cement layer. White spherical particles of fly ash are seen attached to the cement and silica fume matrix [39]. The SEM images clearly show the close, tight packing of the mineral admixtures with the cement particles.

From the Figure 6, 2.5kx, 5kx, and 7.5kx SEM images of normal concrete mix specimen, it is discerned that higher amount of fly ash is bound with the cement particles and that the silica fumes occur in the form of white collated balls. Silica, iron, alumina, and carbon constitute 2.49%, 0.26%, 0.25%, and 61.16% respectively of the materials present in the concrete matrix. The composition of the conventional concrete prepared with fly ash and silica fume as admixtures throws light on the binding capability of cement and admixtures with other ingredients and the density of the concrete.

5.4.2. Scanning Electron Microscopic (SEM) analysis of modified ferro slag concrete

SEM analysis was performed on samples of modified ferro slag aggregate concrete (MF30), which is made by adding silica fume and fly ash together with ferro slag aggregate to replace 30% of natural coarse aggregate. The results are shown in Figures 7 and 8. At 2.5kx, 5kx, 7kx, 25kx, and 50kx the magnification, images were taken and examined.

The chemical interaction between SF, FA, and ($Ca(OH)_2$) results in the generation of additional C-S-H gel, contributing significantly to improved strength. According to SEM analysis of the hardened cement paste as shown in Figure 8, the distribution of C-S-H experienced a noticeable reduction at the 28-day stage, attributed to the substitution of cement with fly ash and silica fume. In this particular mix, the formation of C-S-H was limited, possibly due to the presence of unreacted particles. The mix's microstructure showed very little accumulation of other important mineral components, like crystals of calcite ($CaCO_3$) and $Ca(OH)_2$. The principal cause of the observed reduction in strength was inadequate hydration of the particles inside the matrix of hardened cement. The main element influencing this mix's strength turned out to be the chemical response between $Ca(OH)_2$ and fly ash and silica fume that produced more C-S-H gel.

The SF and FA particle arrangement in the modified ferro slag aggregate concrete is shown in scanning electron microscope (SEM) photos, highlighting the particles strong association with the ferro slag aggregate. Mineral admixtures are added to concrete to improve its density and reduce porosity. Whereas silica fume appears

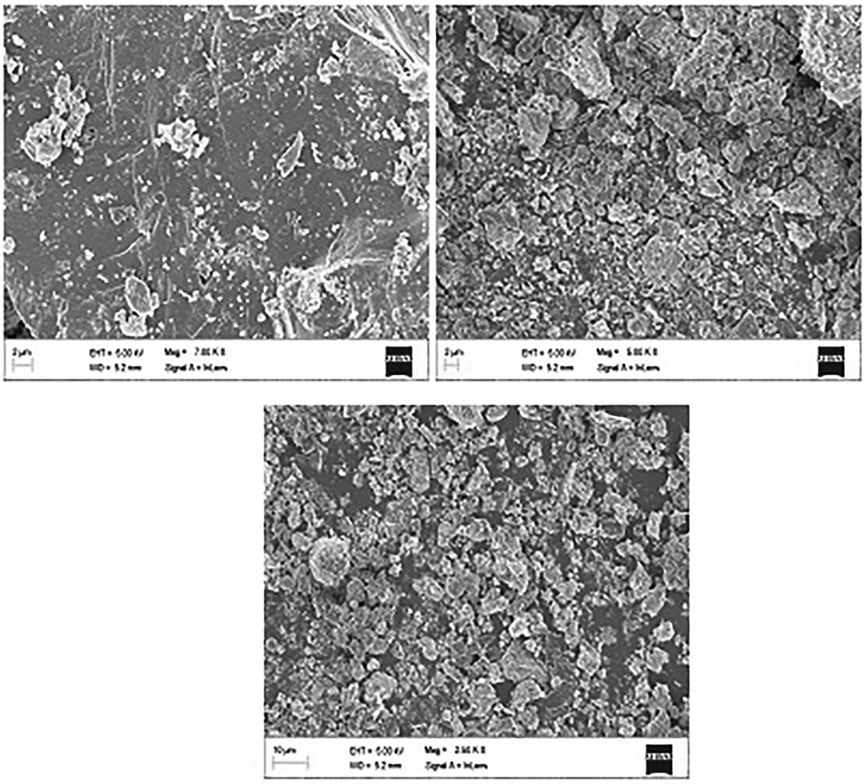

Figure 6: SEM images of conventional concrete at 7kx, 5kx and 2.5kx magnifications.

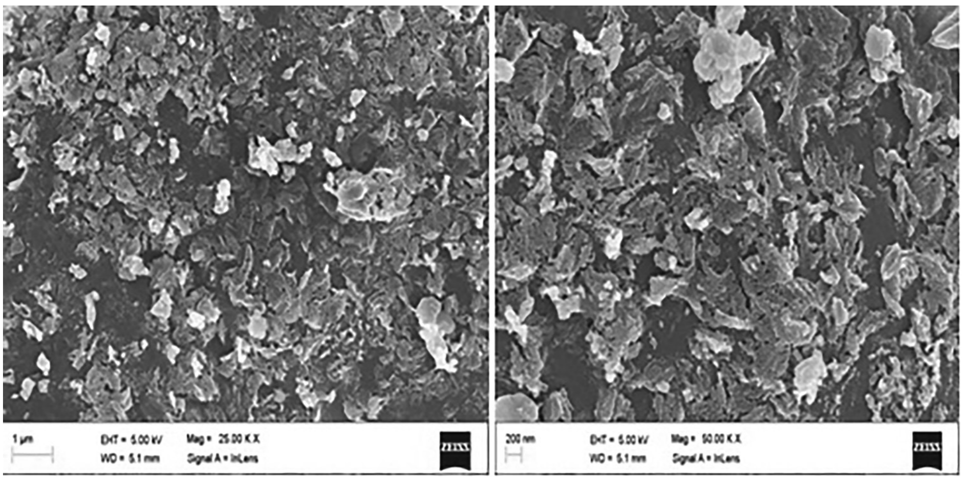

Figure 7: Images of SEM at 25kx and 50kx magnification of modified ferro slag concrete.

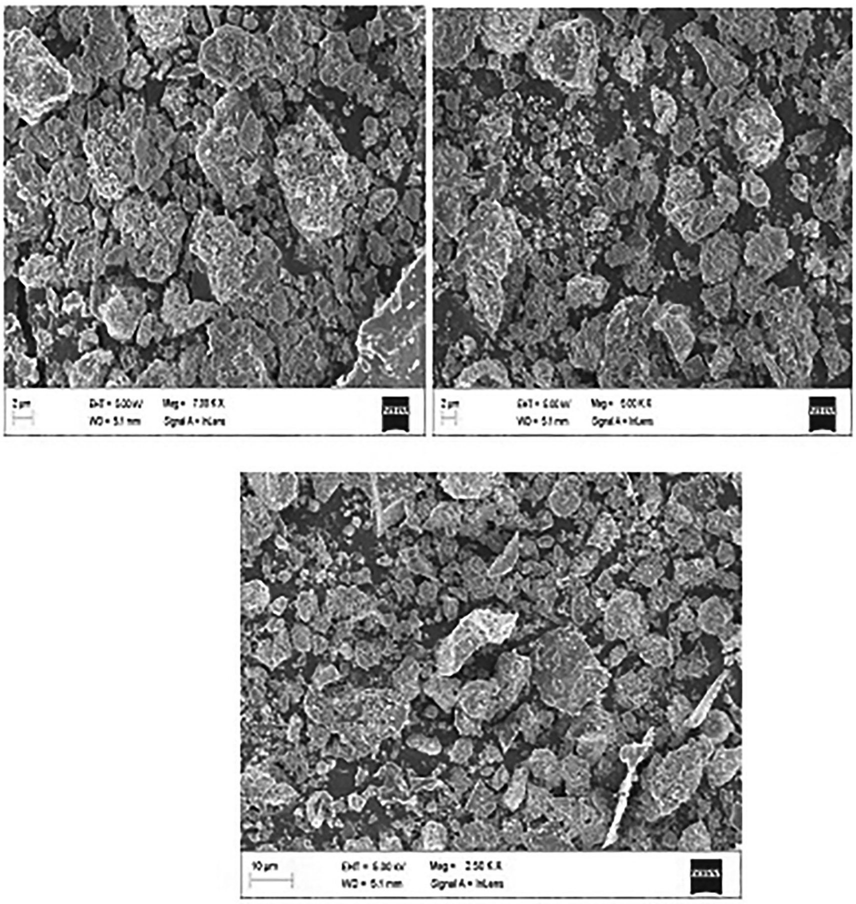

Figure 8: Scanning Electron Microscopic (SEM) images of modified ferro slag concrete at 7kx and 5kx and 2.5kx magnifications.

as white solid ruptured particles, fly ash appears in the concrete matrix as little hollow spherical particles. By utilising its cementitious qualities, silica fume strengthens the links it forms with other constituents, so increasing the concrete mix's impermeability, strength, and density. Modified ferro slag aggregate usually has a silica percentage of 29.40%, which is sophisticated than that of regular concrete. Among the total material content in modified ferro slag concrete, iron, alumina, and carbon constitute 8.82%, 3.36%, and 12.18%, respectively. When analysing the internal structure, chemical makeup, size, shape, orientation, and particle binding of concrete mixes, the scanning electron microscope is a useful tool [40]. The enhanced strength of the modified ferro slag concrete mix (MF30) is evident from high-resolution SEM pictures comparing it to the standard concrete mix.

5.5. Flexural behaviour

5.5.1. Load-deflection details of the different mixes

The values of the load–deflection of the beam section was furnished in Table 10. The results were graphically presented in Figure 9. The loading was applied at the rate of 1 kN/sec in respect of the concrete beam specimens for all types of concrete mixtures [41]. The experimental findings revealed that the concrete beam specimens from the reinforced modified concrete mix (MF30), which involved a 30% replacement of natural aggregate with ferro slag aggregate, endured a advanced static load of 26 kN and exhibited a mid-span deflection of 6.2 mm [42, 43]. The loading capacity of beam of MF30 was somewhat higher than that of the beam of normal concrete mix (MF0). This improvement was due to the sound binding of cementitious material such as silica fume with ferro slag aggregate and other constituents of the concrete mix. The FS of the concrete was generally better in the beams made of all ferro slag aggregate concrete mixes than in the beams made of regular concrete mix [44].

Table 10: Load vs deflection values of beams of different mixes.

SL. NO.	MF0 (100% NA AND 0% FSA AGGREGATE)		MF20 (80% NA + 20% FSA)		MF30 (70% NA + 30% FSA)		MF40 (60% NA + 40% FSA)	
	LOAD (kN)	DEFLECTION (mm)	LOAD (kN)	DEFLEC-TION (mm)	LOAD (kN)	DEFLEC-TION (mm)	LOAD (kN)	DEFLEC-TION (mm)
1	1	0	1	0	1	0	1	0
2	2	0.1	2	0	2	0	2	0
3	3	0.2	3	0.1	3	0.1	3	0.1
4	4	0.4	4	0.2	4	0.1	4	0.3
5	5	0.6	5	0.4	5	0.2	5	0.4
6	6	0.8	6	0.6	6	0.3	6	0.5
7	7	1	7	0.6	7	0.3	7	0.7
8	8	1.1	8	0.7	8	0.4	8	1
9	9	1.1	9	0.8	9	0.4	9	1
10	10	1.3	10	1	10	0.5	10	1.1
11	11	1.5	11	1.2	11	0.6	11	1.2
12	12	1.6	12	1.4	12	0.7	12	1.2
13	13	1.6	13	1.6	13	1.1	13	1.3
14	14	1.8	14	1.8	14	1.2	14	1.3
15	15	2.2	15	2	15	1.3	15	1.4
16	16	2.4	16	2.1	16	1.5	16	1.4
17	17	2.6	17	2.2	17	1.8	17	1.5
18	18	3.2	18	2.6	18	2.5	18	1.6
19	19	3.4	19	2.9	19	2.8	19	1.7
20	20	3.6	20	3.5	20	3.2	20	1.8
21	21	3.8	21	3.6	21	3.6	21	2.1
22	21	4.1	22	3.6	22	3.9	22	2.3
23	22	4.4	23	3.8	23	4.1	23	2.4
24	20	4.6	23	3.8	24	4.3	24	2.5
25	19	5.1	22	4.2	26	5.3	22	2.9
26	18	5.9	20	4.5	23	5.3	19	3.2
27	17	6.5	19	5	20	5.6	18	3.6
28	16	7.8	19	5.2	19	5.7	16	4.1
29	15	8.1	18	5.9	16	5.8	15	4.2
30	15	8.2	17	6	15	6.2	15	4.9

NA = Natural Aggregate, FSA = Ferro Slag Aggregate.

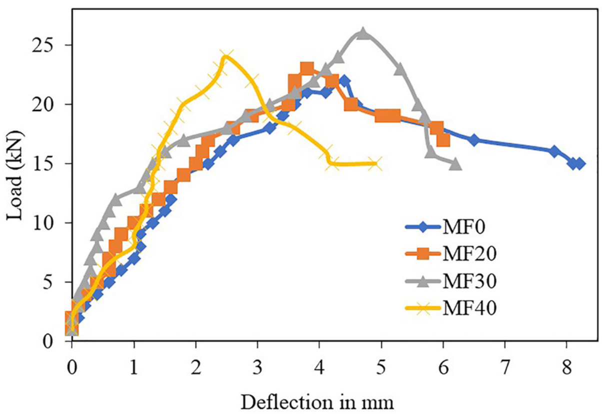

Figure 9: Load vs. deflection for beams of different mix proportions.

6. CONCLUSION

Based on the experimental findings, the following conclusions were drawn.

1. Substituting 30% of the natural aggregate in the concrete mixture with ferro slag noticeably improved its compressive strength, achieving a notable value of 71.22 MPa. However, when the proportion of ferro slag was raised to 40%, a gradual decrease in compressive strength was observed.
2. MF30 attained peak compressive strengths of 71.22 MPa and 72.1 MPa after 28 and 56 days of curing, respectively. This represents a 10% and 11% increase compared to the control mix (MF0).
3. The strong bonding between ferro slag, cement, fly ash (FA), and silica fume (SF) during the hydration process significantly enhanced the concrete's compressive strength. Moreover, the inclusion of ferro slag contributed to the formation of high-density concrete.
4. MF30 achieved split tensile strengths of 3.21 MPa after 28 days of curing and 3.5 MPa after 56 days, representing increases of 6% and 13% compared to the control mix (MF0). The combination of fly ash, silica fume, and ferro slag improved concrete density and split tensile strength by filling the pores.
5. Mix ID MF30 exhibited improved flexural strengths of 6.4 MPa at 28 days and 6.70 MPa at 56 days. These values represent increases of 4% and 9%, respectively, compared to the control mix (MF0) at the corresponding curing periods.
6. The addition of silica fume and fly ash to the concrete mix significantly improves the microstructure of the concrete. SEM analysis revealed a dense and compact microstructure with excellent bonding between cement particles, silica fume, and fly ash. This dense structure contributes to the enhanced mechanical properties of the concrete.
7. The use of ferro slag as a partial replacement for natural aggregate results in a microstructure with improved bonding between the aggregate and the cement paste. The formation of hydration products at the surface of the steel slag particles contributes to a stronger bond with the surrounding cement gel, leading to enhanced overall concrete performance.
8. The incorporation of modified ferro slag aggregate can potentially improve concrete performance due to its higher silica content. The strong association between mineral admixtures and the ferro slag aggregate, as observed in SEM images, suggests a potential for enhanced bonding and improved microstructure.
9. The concrete beam specimens made with 30% ferro slag replacement (MF30) exhibited superior load-bearing capacity compared to the control mix (MF0). This improvement can be attributed to the effective bonding between the ferro slag aggregate and the cementitious matrix, resulting in increased strength and stiffness of the concrete beams.
10. Based on research findings HPC modified with ferro slag aggregates and admixtures can be supported by its industrial applications, such as in high-durability infrastructure like bridges and marine structures, where it enhances strength and longevity.

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