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Synthesis and characterization of strontium hexaferrite composite magnetic materials: A review

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ABSTRACT

$SrCo_xFe_{12-x}O_{19}$ is a composite magnetic material that has wide applications in the field of modern technology. This study aims to synthesize and characterize $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3) using coprecipitation technique and high temperature sintering. The results showed that increasing cobalt (Co) concentration enhanced the magnetic properties of the composite, including saturation magnetization (M_s) up to a peak value of 42.5 emu/g at x = 0.3, as well as higher coercivity (H_c) due to morphological anisotropy and valence change of Fe^{3+} to Fe^{2+}. XRD characterization revealed a magnetoplumbite-type crystal structure with a hexagonal M phase, while FTIR analysis identified Fe–O and Co–O bond vibrations that became more intense with the addition of Co. SEM showed morphological changes from lamellar shapes to small spherical particles as Co increased. VSM analysis confirmed the strong interaction between the hard ($SrFe_{12}O_{19}$) and soft ($CoFe_2O_4$) magnetic phases, which supports the application of this composite as a microwave absorbing material. These findings highlight the potential of $SrCo_xFe_{12-x}O_{19}$ as an advanced magnetic material with characteristics that can be optimized for high-tech applications.

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1. INTRODUCTION

Magnetic materials have emerged as a focal point in materials research owing to their extensive applications in contemporary technology. Ferrite compounds are a fascinating category of magnetic materials. Ferrites are compounds composed of transition metals, including iron (Fe), that bond with oxygen and exhibit magnetic properties applicable in diverse uses. A specific form of ferrite recognised for its robust and steady magnetic properties is SrCoxFe12-xO19, commonly known as strontium hexaferrite.This chemical structure comprises cobalt (Co) and iron (Fe) as the primary components, coupled with the inclusion of the alkaline earth element strontium (Sr). This material is extensively utilised in several applications, including data storage, sensors, and electromagnetic components.

The characteristics of magnetic, dielectric, and microwave absorption can be improved via the interaction between hard and soft magnetic phases. Consequently, magnetic nanocomposites exhibiting high coercivity are becoming increasingly appealing for application as microwave-absorbing materials, primarily owing to the presence of both hard and soft magnetic phases within the compounds. Cobalt ferrite is a category of soft magnetic material frequently employed as a radar-absorbing substance. Strontium hexaferite particles constitute a category of hard magnetic materials, possessing the capability to offer diverse sorts of inequivalent sites for distinct magnetic or non-magnetic cations. Strontium hexapherite is synthesised using many techniques, including the ceramic method, sol-gel method, solid-state approach, and radio frequency sputtering. Methods of synthesis that allow for the simultaneous precipitation of many substances from a solution into a single container offer numerous advantages compared to conventional preparation techniques. The synthesis of SrCoxFe12-xO19 served as a magnetic substrate in various synthesis processes. The coprecipitation method, a synthetic technique for simultaneously precipitating multiple substances from a solution into a single container, is complemented by high-temperature sintering, which is more straightforward and cost-effective.

2. THEORITICAL REVIEW

2.1. Magnetic Substance

Magnetic material is a substance that can generate magnetic fields or react to them. The magnetic qualities originate from the existence of magnetic moments in the component atoms. Materials are categorised into three kinds according to their magnetic properties: ferromagnetic, paramagnetic, and diamagnetic. Ferromagnetic materials possess robust and enduring magnetic characteristics. Examples encompass iron, nickel, cobalt, among others. Paramagnetic materials have a weak attraction to magnetic fields. Upon the removal of the external magnetic field, the magnetisation will dissipate. Examples encompass aluminium, platinum, and oxygen. Diamagnetic materials are substances that exhibit negligible magnetic characteristics or are not susceptible to attraction by magnetic fields. All materials have diamagnetism; however, the effect is so minimal that it is frequently obscured by other magnetic characteristics. Examples include gold, copper, and water.

2.2. Magnetic Characteristics

A magnet is an item capable of attracting surrounding objects. Magnetic objects, or ferromagnetic materials, include iron, nickel, cobalt, and certain metals that can be attracted by magnets. Objects that cannot be attracted by magnets are referred to as non-magnetic objects (diamagnetic), including materials such as copper, aluminium, plastic, and rubber [4]. Magnetic properties denote the attributes of materials that can display magnetic behaviour when subjected to a magnetic field. In the realm of magnetic nanoparticles, essential properties to consider are magnetic susceptibility, magnetic moment, and magnetic anisotropy.

2.2.1. Magnetic Susceptibility

Magnetic susceptibility quantifies a material's ability to be polarised by a magnetic field.This magnetic susceptibility delineates the reaction of materials to magnetic fields, which can be categorised into numerous forms, namely:

2.2.1.1. Ferromagnetism

Ferromagnetic materials possess a significantly high susceptibility and can retain magnetisation long after the external magnetic field is eliminated. Ferromagnetic refers to a category of materials that exhibit a significant attraction to magnetic fields. A ferromagnetic object in proximity to a magnet will be attracted to it. Ferromagnetic materials include steel, iron, nickel, and cobalt.

2.2.1.2. Paramagnetic

Paramagnetic refers to a substance exhibiting positive susceptibility, characterised by a weak attraction to magnetic fields. Examples of paramagnetic materials include copper, aluminium, and platinum.

2.2.1.3. Diamagnetic

Diamagnetic refers to a category of materials that demonstrate a repulsive response to magnetic fields. This category of diamagnetic material is impervious to attraction by a magnet, regardless of proximity to a powerful magnet. Instances of diamagnetic substances include zinc, sodium chloride, and bismuth.

2.2.2. Magnetic Moment

The magnetic moment quantifies the intensity and orientation of a magnetic source. Magnetic moments are affected by particle dimensions and crystalline structure. The magnetic moment (μ) can be determined by the quantity of electron spins and electron orbitals present in the material. Electron spins are the inherent motion of electrons that generate magnetic moments, whereas electron orbitals refer to the trajectories of electrons. Electrons orbiting the atomic nucleus contribute to the formation of magnetic moments. The magnetic moment (μ) is represented by the subsequent formula:

$$\mu = \frac{-e}{2m_e}L \tag{1}$$

where, magnetic moment (measured in joules per tesla or ampere-square metre), electron charge is 1.602×10^{-19} coulombs, electron rest mass is 9.109×10^{-31} kg, and angular momentum can arise from two forms of rotation (spin rotation and the rotation of electron orbitals).

2.2.3. Magnetic Anisotropy

Magnetic anisotropy refers to the directional dependence of a material's magnetic properties. In this application, anisotropy denotes the fluctuation in magnetic energy encountered by a material when its magnetic moment is orientated in various directions. The energy of magnetic anisotropy influences the stability and reaction of the material to magnetic fields.

2.3. Strontium Hexaferrite ($SrCo_xFe_{12-x}O_{19}$)

Strontium hexaferrite ($SrCo_xFe_{12-x}O_{19}$) is a cobalt-containing ferrite compound characterised by a hexagonal crystal shape. Strontium hexaferite is a ceramic substance composed of permanent magnets.

3. RESEARCH METHODS

3.1. High-Temperature Sintering Coprecipitation Technique

This method employs a chemical process in which the initial substance dissolves in a liquid and subsequently transforms into solid particles via a chemical reaction. Subsequently, the synthesised particles are subjected to drying and elevated temperatures to enhance their density and magnetic characteristics. This procedure enables precise regulation of the composition.

3.1.1. Sol-Gel Technique

The sol-gel method is a methodology for synthesising materials that transitions from a solution (sol) to a solid network (gel). In this method, chemicals are dissolved in a sol to create a sol, which subsequently polymerises into a gel. Subsequently, the gel is dehydrated and subjected to heat to eliminate the solvent and induce crystallisation of the substance. The sol-gel technique is frequently employed to synthesise compounds characterised by diminutive particle size and uniform dispersion.

3.1.2. Ceramic Technique

The ceramic method is a conventional process that entails combining dry ingredients (powders), which are subsequently moulded and subjected to high temperatures. This technique yields materials with stable crystalline structures and excellent mechanical characteristics. This technique is frequently employed to produce ferrite and various ceramic materials.

3.1.3. Sintering Procedure

The sintering process involves heating a material to a high temperature below its melting point, aimed at consolidating its particles into a stronger, more durable, and harder mass. The sintering process in ceramic materials occurs exclusively at specific temperatures [3]. The sintering process of $SrCo_xFe_{12-x}O_{19}$ composite magnetic material employs the chemical coprecipitation technique. The subsequent steps of the sintering process are as follows:

- Preparation of Powder: Subsequent to the coprecipitation process, the resultant material is desiccated and pulverised into a fine powder.
- Sintering: The fine powder is thereafter heated to a high temperature of 1000°C for a duration of 2 hours. The sintering process seeks to amalgamate powder particles into a more compact structure

and enhance interparticle interactions, hence potentially augmenting the magnetic characteristics of the resultant material.

- Impact of Sintering: The sintering process diminishes the non-magnetic phase while augmenting the magnetic phase, resulting in materials with enhanced magnetic characteristics, including elevated saturation magnetization [5].

3.2. Characterisation of Magnetic Materials

The characterisation of $SrCo_xFe_{12-x}O_{19}$ composite magnetic material was conducted utilising several techniques to examine the structure, morphology, and magnetic characteristics of the synthesised material.

3.2.1. X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is a widely utilised technique for material characterisation. This technique is employed to ascertain the crystal structure of the composite [1]. The XRD data indicate that the composite possesses a mineral oxide crystalline structure accompanied by a secondary phase. Diffraction peaks are identified to verify the existence of these phases and yield information regarding the lattice parameters and crystallite size [4].

3.2.2. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a technique employed to concurrently and quantitatively identify chemical structures based on atomic vibrations. FTIR generates peaks and spectra that function as distinctive identifiers of molecular structures and specific chemical bonds inside a substance, particularly in the examination of plastics, polymers, and organic constituents [3]. FTIR is employed to identify functional groups and bonds inside materials. The FTIR spectrum reveals distinctive peaks corresponding to $SrCo_xFe_{12-x}O_{19}$ and CoO, along with stretching vibrations from hydroxyl groups.

3.2.3. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a material characterisation technique extensively employed to examine the surface morphology of particles as small as 1 nm. Scanning Electron Microscopy (SEM) is a technique extensively employed in Vibrating Sample Magnetometry (VSM) to analyse the morphology and microstructure of surfaces that are not discernible by the naked eye or optical microscopy, utilising an electron microscope. It offers extensive magnification and three-dimensional pictures that facilitate the observation and analysis of sample characterisation results [2].

3.2.4. Vibrating Sample Magnetometer (VSM)

The Vibrating Sample Magnetometer (VSM) is a device utilised to test and ascertain the magnetic characteristics of a substance. Faraday's law of electromotive force (e.m.f), induced in a conductor by variations in magnetic flux, underpins the operation of VSM. The Vibrating Sample Magnetometer (VSM) comprises three essential components for measuring the magnetic properties of materials: the magnetic sample, electromagnet, and detection coil (pick-up coil). These components are symmetrically arranged, with the pick-up coil positioned parallel to the magnetic field direction. Magnetic samples are materials subjected to analysis to ascertain their magnetic characteristics. The electromagnet serves to produce the magnetic field necessary for measurement. The detection coil (pick-up coil) is employed to identify the signal produced by the sample as it oscillates within the magnetic field. The VSM method effectively measures the magnetic characteristics of materials. The operational idea of VSM is straightforward: the magnetic sample is positioned on a sample rod, referred to as a sample holder, and thereafter oscillated using a mechanical vibrator at a specified frequency. The sample is positioned between two polar electromagnets, with the detection coil, or pick-up coil, symmetrically arranged relative to the sample's location. The oscillatory motion of the magnetic sample will cause an induced voltage in the detection coil. The induced voltage, proportionate to the sample's magnetisation, is achieved by varying the strength of the external magnetic field produced by the electromagnet, leading to a hysteresis curve, which reflects the magnetisation induced by the external magnetic field.

4. RESULTS AND DISCUSSIONS

4.1. Fourier Transform Infrared Spectroscopy and X-ray Diffraction Analysis of Products

$SrCo_xFe_{12-x}O_{19}$ (x=0–0.3) was synthesised using the coprecipitation high-temperature sintering technique. This experimental procedure demonstrated the ability to enhance mass production. Figure 1 illustrates the infrared (IR) spectrum of synthesised $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

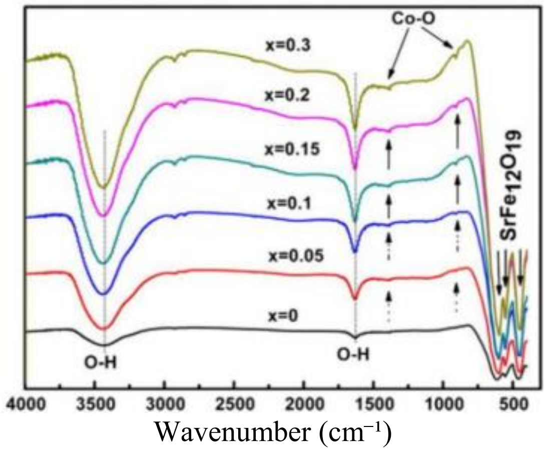

Figure 1. Infrared (IR) spectrum of $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

The figure displays maxima at approximately 598 cm^{-1}, 551 cm^{-1}, and 440 cm^{-1} within the range of 400 cm^{-1} to 800 cm^{-1} for each curve. The IR spectra of standard CoO and Co_2O_3 exhibit peaks at around 1375 cm^{-1} and 875 cm^{-1}, which correspond to Co-O stretching vibrations and Co-O anti-symmetric stretching vibrations, respectively, in each curve except for the x = 0 curve. The two peaks will intensify and sharpen as x values increase (Figure 1), however they remain relatively subdued due to the limited quantity of Co. With the increasing addition of Co, the peaks at 598 cm^{-1}, 551 cm^{-1}, and 440 cm^{-1} intensify and sharpen. Moreover, the presence of Co^{2+} enhances the chemical polarisation of the links in $SrFe^{12}O^{19}$. Consequently, the oxygen atom in the Fe(Sr)-O bond can be dissociated from the Co atom, potentially influencing the vibrational interaction between Fe(Sr)-O and Co-O. It may be concluded that $SrCo_xFe_{12-x}O_{19}$ was successfully synthesised via the coprecipitation high-temperature sintering technique.

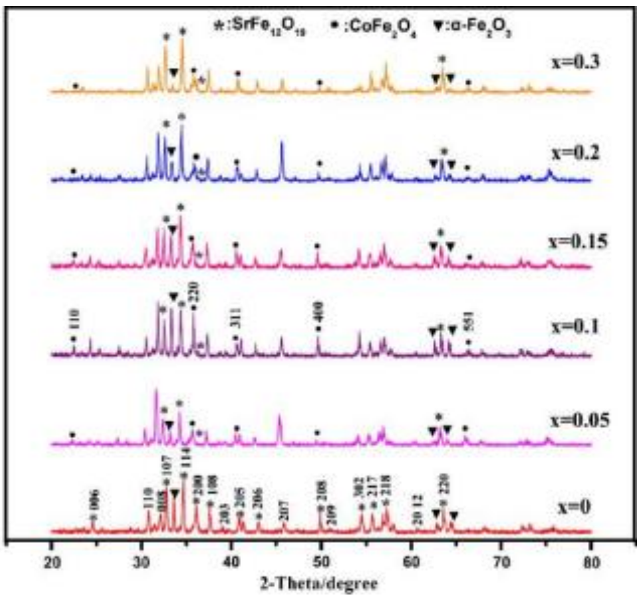

Figure 2. XRD pattern of $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

Figure 2 illustrates the XRD pattern of the synthesised $SrCo_xFe_{12-x}O_{19}$. The composite has hard and soft magnetic phases, with the magnetic moment of Co^{2+} being inferior to that of Fe^{3+}. The peaks observed in the XRD patterns intensify and sharpen as cobalt content increases. The synthesised composites exhibit potential as effective magnetic substrates, with enhanced magnetic characteristics corresponding to increased cobalt content.

4.2. Product Scanning Electron Microscopy Analysis

Figure 3 illustrates that the morphology of the different samples analysed using the SEM method has been created.

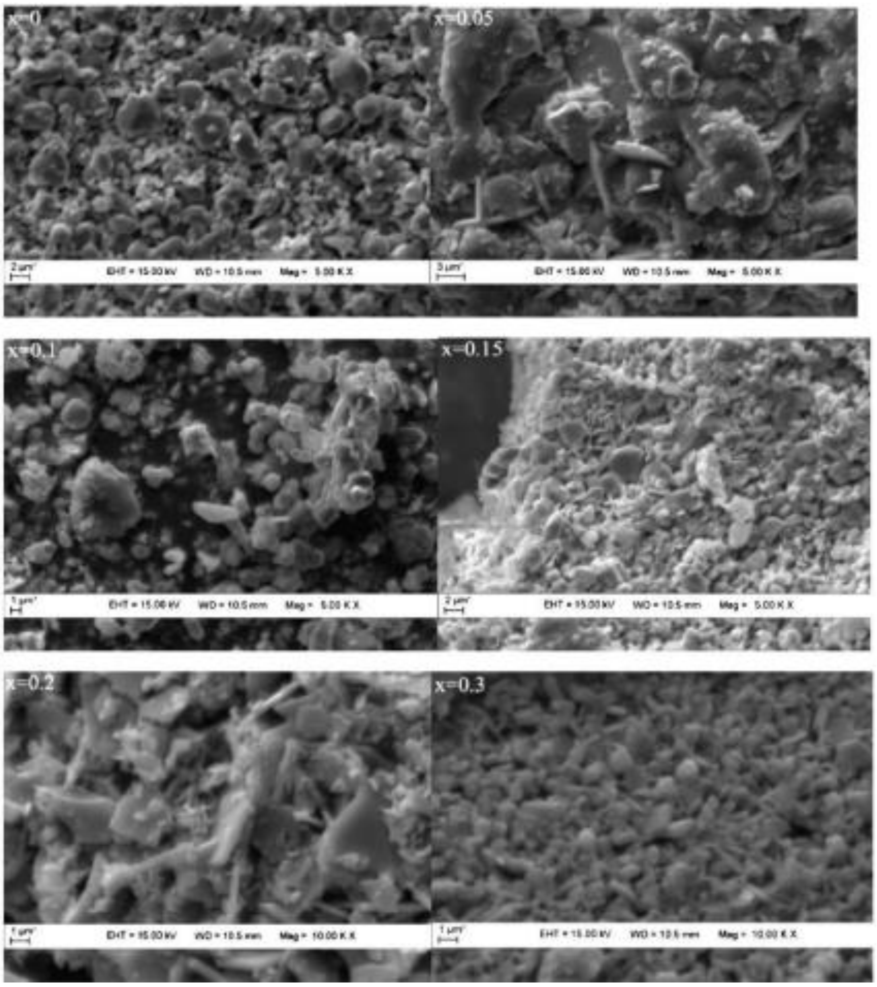

Figure 3. SEM image of $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

The morphology consists of minute needle-shaped and spherical particles resembling granules, as illustrated in Figure 3 (x = 0.15, 0.2, 0.3). The composite with x = 0.05 exhibits lamellar-shaped particles, whereas the composites with x = 0.15 to x = 0.3 have more rounded and diminutive particles. The outcomes align with the findings from XRD and IR analyses. The molecular mass of SrFe12O19 exceeds that of $CoFe_2O_4$, suggesting that $SrFe_{12}O_{19}$ has a greater capacity to absorb electrons compared to $CoFe_2O_4$. Consequently, the $SrFe_{12}O_{19}$ area has a dark hue, whilst the $CoFe_2O_4$ area seems relatively bright. Due to the absence of a surfactant during the experiments or the heating of the powder at 1000°C, nearly all the particles aggregated.

4.3. Product Value Stream Mapping Analysis

The magnetic characteristics of the products, as determined by VSM, together with the results, are illustrated in Figure 4.

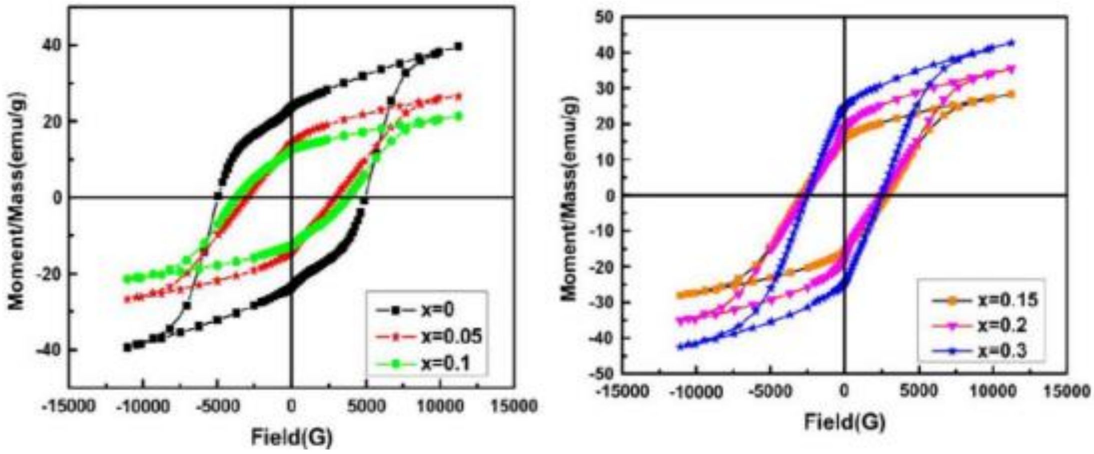

Figure 4. Magnetic hysteresis loop of $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

Figure 4 illustrates the magnetic hysteresis loop of the $SrCo_xFe_{12-x}O_{19}$ composite with differing cobalt concentrations (x=0–0.3). The picture illustrates that an increase in cobalt content correlates with elevated saturation magnetisation (M_s) and coercivity (H_c) values. The resultant loop configuration exhibits ferromagnetic properties, with a concave demagnetisation curve signifying interaction between the hard and soft magnetic phases in the composite. These samples exhibit comparatively elevated saturation magnetisation (M_s) and remanent magnetisation (M_r). Consequently, the x = 0.15 composite is less than the x = 0 powder, while also inferior to the hard phase, and vice versa. The synthesised $SrCo_xFe_{12-x}O_{19}$ is classified as a nanomaterial due to its reduced crystal size. This indicates the presence of $CoFe_2O_4$ in the synthesised composite.

Table 1. The magnetic characteristics of $SrCo_xFe_{12-x}O_{19}$ (x=0–0.3).

$SrCo_xFe_{12-x}O_{19}$	Saturation Magnetisation (emu/g)	Remanent Magnetisation (emu/g)	Coercivity (Oe)
x = 0	39.6	23.9	4876
x = 0.05	26.3	14.7	2889
x = 0.1	21.4	12.3	3857
x = 0.15	28.3	15.9	2870
x = 0.2	35.3	18.6	2475
x = 0.3	42.5	25.1	2475

To diminish or eradicate the magnetic characteristics of an ideal material within a composite system comprising hard and soft magnetic phases, theoretical research indicates that the critical dimensions of the soft magnetic phase must be less than twice the domain wall width of the hard phase, while the hard magnetic phase should match the critical size of the soft magnetic phase. The domain wall width of the hard magnetic phase, strontium hexaferrite, measures around 11 nm. The soft magnetic phase, cobalt ferrite, possesses a size range of 30 – 50 nm, exceeding the critical limit. The dimensions of the hard magnetic phase, strontium hexaferrite, are 455 angstroms (45.5 nm), where the dimensions are significantly more essential.

Consequently, to diminish or eradicate the magnetic properties of a material, the hard and soft magnetic phases coexist indistinctly, producing a distinctive curve shape that serves to reduce or eliminate the magnetic properties of a material, characterised by concavity in the second and fourth quadrants of the hysteresis loop, referred to as the exchange behaviour of the spring.

5. CONCLUSION

The magnetic characteristics of the $SrCo_xFe_{12-x}O_{19}$ (x = 0.3) composite exhibit considerable improvement with elevated cobalt (Co) concentration. This enhancement entails an augmentation in saturation magnetisation (M_s), with a peak value of 42.5 emu/g for x = 0.3, alongside enhanced coercivity (H_c) attributed to morphological anisotropy and valence alterations from Fe^{3+} to Fe^{2+}

induced by Co doping. The composite's dual-phase structure, consisting of a hard magnetic phase ($SrFe_{12}O_{19}$) and a soft magnetic phase ($CoFe_2O_4$), enhances its exceptional magnetic and dielectric absorption characteristics, rendering it appropriate for applications like microwave-absorbing materials. The characterisation techniques corroborate these findings. X-ray diffraction (XRD) indicates a magnetoplumbite-type crystalline structure characterised by a hexagonal M phase. Fourier transform infrared spectroscopy (FTIR) detects distinctive Fe-O and Co-O bond vibrations, which amplify with increased Co concentrations. Scanning electron microscopy (SEM) reveals morphological alterations, shifting from lamellar to rounded tiny particles with increasing Co content. The vibrating sample magnetometer (VSM) study indicates the peak M_s value at $x = 0.3$, underscoring robust interactions between the hard and soft magnetic phases. The thorough characterisations highlight the composite's potential for sophisticated magnetic applications.

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