Phase and Magnetic Properties of Fe₃O₄/SiO₂ Natural Materials-Based Using Polyethylene Glycol Media

Munasir¹², N. Setyaningsih¹, S. Yanasin¹, and Z.A.I. Supardi¹², A. Taufiq³, Sunaryono³

¹ Department of Physics, Faculty of Mathematics and Natural Science, Universitas Negeri Surabaya, Kampus Ketintang, Jl. Ketintang, Surabaya, 60231
² Research Center of Advanced Materials, Universitas Negeri Surabaya, Kampus Ketintang, Jl. Ketintang, Surabaya 60231.
³ Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang, Jl. Semarang No 5, Malang 65145, Indonesia

* Corresponding author’s email: munasir_physics@unesa.ac.id

Abstract. The research objectives were phase characterization and magnetic properties of Fe₃O₄/SiO₂ nanocomposite (NCs) prepared by a wet-mixing process so that Fe₃O₄ magnetite nanoparticles coated amorphous silica SiO₂; Polyethylene glycol is used as a binding medium. The Fe₃O₄ magnetic material was prepared from the iron sand with a co-precipitation method and silica (SiO₂) nanoparticles from quartz sand with a continuous method (hydrothermal-coprecipitation). The samples were characterized using X-ray diffraction (XRD), Fourier transformed infrared spectroscopy (FTIR), and vibrating sample magnetometers (VSM). The data analysis of the XRD and FTIR data presented that the Fe₃O₄ and SiO₂ crystals were obtained which respectively act as the Fe₃O₄/SiO₂ NCs; signified by the existence of silanol (Si-O; O-Si-O) and Fe^{2+} (Fe-O) functional groups. The VSM profile exhibited the superparamagnetic/soft-magnetic properties at room temperature. The presence of the silica shell is able to decrease the magnetization from 29 emu/g to 5 emu/g.

Keywords: Nanocomposite (NCs), Fe₃O₄/SiO₂, soft-magnetic, PEG.

1. Introduction

In the 1980s, material engineering was invented with a combination of two or more materials into composite nanoparticles that have better characteristics than nanoparticles of one type of material, known as nanocomposite materials [1,2]. And in the 1990s, multilayer semiconductor nanoparticles were successfully synthesized to improve the properties of the semiconductor material, from which the term core-shell NPs emerged [2,3]. The material structure consists of a core as the core existing inside and the shell as the outer layer as a core cell wrapper [3]. The properties of nanoparticles do not only depend on the size but also the form. For example, the properties of magnetic nanoparticles depend on the shape of the particles due to anisotropic surface effects. Thus, nanoparticle synthesis in the form of a core-shell can increase the magnetic properties of a material [1–3].

Iron oxide in nature has several forms such as hematite, maghemite, and magnetite. Recently, there have been many studies on magnetic materials, especially Fe₃O₄ magnetite nanoparticles or commonly
written as Fe\textsubscript{3}O\textsubscript{4} MNPs, are superparamagnetic materials, and have high coercivity. To put it simply, magnetite is a reaction result of ferrous oxide (FeO) and ferric oxide (Fe\textsubscript{2}O\textsubscript{3}) [4,5]. Magnetite nanoparticles are formed with the existence of ion Fe\textsuperscript{2+} occupying half of the octahedral lattice and Fe\textsuperscript{3+} occupy another octahedral lattice and in all tetrahedral lattices [6–8]. The magnetite structure is specifically signified with crystal fields of (220), (311), (400), (422), (511), and (440) in the form of inverted cube or spinel; the structure of Fe\textsubscript{3}O\textsubscript{4} MNPs was spinel indicating the crystalline structure Fe\textsubscript{3}O\textsubscript{4} MNPs in (220), (311), (400), (422), (511), and (440) [5]. The main characteristics of Fe\textsubscript{3}O\textsubscript{4} MNPs was non-toxic and biocompatible material [6,7] can be applied as a new-biomedical material such as biosensor, contrast agent in MRI (magnetic resonance imaging), magnetic target in TDD (targeting drug delivery), antibacterial, tissue engineering, magnetofractionation agent, magnetic bioseparation, DNA molecule detection, and hyperthermia [6–10].

Theoretically, the core-shell form can be classified into several types, among them are: single-sphere as a core covered by a shell, multi-sphere as a core covered by a shell, a single hollow-sphere as a core covered by a shell, multi-sphere (a type) as a shell covering the core of the particle (core), the shape of the small sphere as the outer shell of different materials surrounding the core cell (core), the multilayer layer with the outer layer (shell) and core consisting of two layers and the core cell (core) in the form of a solid outer layer (shell) with porous texture, and so on [11,12]. Based on the type of core and shell composing material, it can be divided into four types, including: (i) anorganic/organic, there are two possible formations, namely anorganic/silica (such as Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2}, Ag/SiO\textsubscript{2}, etc.) and anorganic/non-silica (for example Au/Fe\textsubscript{3}O\textsubscript{4}, Fe/Ag, etc.), (ii) anorganic/organic, there are two possible formations of core-shell they are magnetic/organic (such as Fe\textsubscript{3}O\textsubscript{4}/PEG, Fe\textsubscript{3}O\textsubscript{4}/Poly, etc.) and non-magnetic/organic (such as Ag/PEG, SiO\textsubscript{2}/PS, etc.), (iii) core-shell organic/anorganic (such as PEG/SiO\textsubscript{2}, PS/Fe\textsubscript{3}O\textsubscript{4}, etc.), and (iv) core-shell organic/organic (such as Polyphenylene/PEO, PS/NIPA, etc.) [13].

In recent studies, the formation of Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} nanocomposite material is performed with an In-Situ method, with TEOS as the precursor and the coating forming the core-shell [10]. The measurement results of magnetic properties especially in saturation magnetization of Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} NCs powder material decreased in half of the Fe\textsubscript{3}O\textsubscript{4} NPs powder. In addition, the method that has been used to coat and control the thickness of coating for the Fe\textsubscript{3}O\textsubscript{4} core cell with SiO\textsubscript{2}, namely micro-emulsion method, and tetraethyl orthosilicate alkaline hydrolysis (TEOS), or known as Stöber method [4], which was also effective in forming Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} core-shell. NP-shell core that has been coated with surfactant on the surface of the silica, and tetraethyl orthosilicate alkaline hydrolysis is highly promising to produce Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} NCs core-shell without surfactant, but still stable and easy to disperse [6,12,13]. Magnetite Fe\textsubscript{3}O\textsubscript{4} NPs is not stable in the air and tends to form agglomeration formation, the use of Polyethylene-Glycol (PEG) can improve the bond between particles Fe\textsubscript{3}O\textsubscript{4} (as core) and SiO\textsubscript{2} (as shell) particles [14,15].

In this article, we reported the magnetic properties of Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} NCs with the core-shell formation was occupied by Fe\textsubscript{3}O\textsubscript{4} NPs, and the shell was coated by SiO\textsubscript{2} NPs, a one-pot wet mixing method was used with PEG as the binder. Material functional Fe\textsubscript{3}O\textsubscript{4} NPs and amorphous SiO\textsubscript{2} NPs were prepared from natural mineral materials, through a simple extraction process and synthesis (co-precipitation); structural studies with XRD and functional groups with FTIR data and magnetic properties with VSM and Bartington MS\textsubscript{2}B tests on Fe\textsubscript{3}O\textsubscript{4}/SiO\textsubscript{2} NCs material were the focus of this report.

2. Methods

The basic materials provided were natural iron sand material (~40% iron oxide), and silica sand (~70% oxide silica, quartz), PEG 4000, and other chemical materials for synthesis process namely hydrochloride acid (HCl) PA (37%), NH\textsubscript{4}OH, NaOH, and aquades. Fe\textsubscript{3}O\textsubscript{4} nanoparticles were prepared from the extraction process of raw material iron sand (~30–40%), the first stage was performing the separation of iron grains from its impurities (washed and magnetically separated). The dissolution of iron oxide (~80–90%) with HCl (12 M), added NH\textsubscript{4}OH base solution slowly (co-precipitation process), the formation of sediment, washed and dried, Fe\textsubscript{3}O\textsubscript{4} NPs powder was obtained [16].

SiO\textsubscript{2} nanoparticles were prepared with the continuum method (hydrothermal and co-precipitation). The initial stage of the separation of quartz grains from the impurities, then the hydrothermal process
with an alkaline NaOH (7M) compound, the formation of a glass solution precursor (Na$_2$SiO$_3$), then proceeded with a co-precipitation HCl solution (12 M). SiO$_2$-NPs was gained [17]. Fe$_3$O$_4$/SiO$_2$ nanocomposites were performed by a wet-mixing method using Polyethylene Glycol (PEG) 4000 –0.5 gram as its binder, with the comparison of Fe$_3$O$_4$ and SiO$_2$ was 1:1, with the wet-mixing or one-pot process method, as illustrated in Figure 1. The Fe$_3$O$_4$ powder and SiO$_2$ as well as Fe$_3$O$_4$/SiO$_2$ NCs as the final product, the sample was ready to be characterized. The samples were characterized using XRD, FTIR, and VSM.

3. Results and Discussion
The results of XRD testing on Fe$_3$O$_4$-NPs and Fe$_3$O$_4$/SiO$_2$ NCs samples are presented in Figure 2, with referring to the reference data (pdf-database: 01-088-0866) and comparing with the results of previous research [9,18], showed the obtained samples have a Fe$_3$O$_4$ magnetite phase: crystal field (220), (311), (440), (422), (511), (440), (620), (533). At the position of 2θ which ranged about 18-32° indicated the non-crystal (amorphous), SiO$_2$ diffraction pattern [15]. The X-ray diffraction pattern for Fe$_3$O$_4$-NPs sample (Figure 2a) and Fe$_3$O$_4$/SiO$_2$ NCs can be seen in Figure 2 (Figure 2b). The diffraction pattern of Fe$_3$O$_4$/SiO$_2$ NCs can be seen on the field (440) and seemed to be dominant on the other crystal fields (220), (311), (422), (511), (620), and (533). While the effect of using PEG affected the formation of two new peaks in the angle range (2θ): 18-25° [9,18].

![Figure 1. (a) Fe$_3$O$_4$-NPs powder, (b) SiO$_2$-NPs powder, and (c) Fe$_3$O$_4$/SiO$_2$ NCs](image1.png)

![Figure 2. XRD patterns of the Fe$_3$O$_4$-NPs and Fe$_3$O$_4$/SiO$_2$ NCs](image2.png)
Based on the analysis results of the diffraction pattern, it showed that \( \text{Fe}_3\text{O}_4/\text{SiO}_2 \) nanocomposites have been successfully formed indicated with the appearance of the joint peak of \( \text{Fe}_3\text{O}_4 \) and \( \text{SiO}_2 \). Overall, the diffraction pattern analysis of the composite sample is in line with the previous research [19, 20]. The use of PEG in physics does not effect on the crystal properties and structures of \( \text{Fe}_3\text{O}_4/\text{SiO}_2 \) nanocomposites [5,8,15,16,19–21]. Zhang, et al. showed the peak of PEG field on PEG/\( \text{SiO}_2 \) was visible at the position (2\( \theta \)) around 19° and 23° [20]. From previous studies, the presence of PEG has no significant effect on the magnetic properties of \( \text{Fe}_3\text{O}_4/\text{SiO}_2 \), but typical peak form of PEG at 2\( \theta \) =18–32° (see Figure 2(b)) [8,14,15].

As displayed in Figure 3, the infrared absorption spectrum on the wavenumber ranges from 300-2.500 cm\(^{-1}\) (FTIR testing results) of \( \text{Fe}_3\text{O}_4\)-NPs and \( \text{Fe}_3\text{O}_4/\text{SiO}_2\)-NCs; Fe-O group appeared on \( \sim 587 \text{ cm}^{-1} \); at the ranges of 1300-1500 cm\(^{-1}\). There was C-O originated from PEG (the details are presented in Table 1). The results of matching the infra-red wave absorption peaks indicate the type of functional group of \( \text{SiO}_2 \), \( \text{Fe}_3\text{O}_4 \) oxide and \( \text{Fe}_3\text{O}_4/\text{SiO}_2 \) NCs on the results of previous research [21–23].

![Image](b)

**Figure 3.** Wave-numbers IR-Spectral of \( \text{Fe}_3\text{O}_4\)-NPs and \( \text{Fe}_3\text{O}_4/\text{SiO}_2\)-NCs samples

**Table 1.** The IR wave peak on the sample and its matching with references

| Wavenumbers (cm\(^{-1}\)) | Functional Group                        | References                  |
|----------------------------|-----------------------------------------|-----------------------------|
| 469                        | Si-O bond rocking                       | [17, 24]                    |
| 587                        | Vibration of Fe-O-Fe group              | [26, 27, 28]                |
| 812                        | O-H bond                                | [24, 27]                    |
| 1118                       | O-H bond                                | [24]                        |
| 1352                       | C-O bending                             | [17,24]                     |
| 1649                       | Si–O–Si Asymmetrical vibration          | (24,26)                     |
In Table 1, it can be seen at the wavenumbers range between 2.500 cm\(^{-1}\) until 300 cm\(^{-1}\) (measuring range): there was a characteristic from SiO\(_2\): Si-O functional group bond-rocking vibration at the wavenumber of 469 cm\(^{-1}\) and Si-O-Si asymmetric vibration on 1649 cm\(^{-1}\) [17,21,23]. Then, the O-H bond (water molecule) was found in the range of wavenumbers of 800-870 cm\(^{-1}\) [24]; the vibration of the C-O bond at the wavenumbers of 1351 cm\(^{-1}\) and 1637 cm\(^{-1}\) [24,25]. Therefore, the FTIR testing results can strengthen that the Fe\(_3\)O\(_4\)/SiO\(_2\)-NCs has been formed, which is characterized by the presence of silanol groups, siloxanes, and Fe-O-Fe vibration groups.

In Figure 4, the magnetization hysteresis curve of Fe\(_3\)O\(_4\)-NPs and Fe\(_3\)O\(_4\)/SiO\(_2\) NCs samples, the effect of SiO\(_2\) addition was suspected to be able to decrease the magnetic properties of Fe\(_3\)O\(_4\), it was suspected that magnetic nanoparticles were coated by SiO\(_2\). This could happen since silica is a non-magnetic material having isolator and inert properties [8,26], protecting of Fe\(_3\)O\(_4\) in a core-shell formation [27], this shows a moderate classification, and still super paramagnetic [28] and soft magnetic materials [29], see Figure 4. From the results of the VSM test, it shows that addition, or coating on Fe\(_3\)O\(_4\) NPs with SiO\(_2\) nanoparticles (amorphous) with a wet-mixing method, was able to significantly reduce and control the magnetic properties, from the magnetization value of 29 emu/g into approximately 5 emu/g.

The VSM test remains the ideal characterization choice for knowing material magnetism. The wider the hysteresis loop shows the value of the magnetic susceptibility is large, otherwise the narrower the hysteresis loop the smaller the magnetic susceptibility value is, the soft magnetic category and hard magnetic [30,31]. The magnetic susceptibility with Bartington technique aimed at identifying the magnetic properties of a material. Based on the susceptibility test, it was obtained the results as in Table 2.
Table 2. The results of magnetic susceptibility testing

| Samples | Fe$_3$O$_4$:SiO$_2$ ratio | $\kappa_{lf}$ | $Z_{lf}$ (×10$^{-3}$ m$^3$/kg) | $\kappa_{hf}$ | $Z_{hf}$ (×10$^{-3}$ m$^3$/kg) | $\chi_{fd}$ (%) |
|---------|---------------------------|----------------|-------------------------------|----------------|-------------------------------|----------------|
| Fe$_3$O$_4$ | -                         | 0.07664        | 0.5435                        | 0.07355        | 0.5216                        | 4.024          |
| #S1     | 1:1                       | 0.03986        | 0.2779                        | 0.03838        | 0.2676                        | 3.723          |
| #S2     | 1:2                       | 0.04083        | 0.2121                        | 0.03876        | 0.2013                        | 5.087          |
| #S3     | 1:3                       | 0.01977        | 0.1380                        | 0.01879        | 0.1312                        | 4.963          |
| #S4     | 3:1                       | 0.05078        | 0.3541                        | 0.04808        | 0.3352                        | 5.325          |

Based on Table 2, from the magnetic susceptibility results, it was obtained several magnitude parameters which were kappa ($\kappa$) and magnetic susceptibility ($\chi$). The $\kappa$ value is the susceptibility volume from the testing sample, while the magnetic susceptibility value ($\chi$) explained that the magnetism intensity ratio affected in a material on its magnetic force [27]. The measurement of a magnetic susceptibility was done using Bartington MS2B which works on two frequencies, namely 470 Hz which is called low-frequency susceptibility value ($\chi_{lf}$) and 4.7 kHz which was the high susceptibility value ($\chi_{hf}$) [28]. The measurement was intended to determine the value of frequency-dependent magnetic susceptibility ($\chi_{fd}$ %). The results of nanocomposite magnetic susceptibility values indicated that the composition variation affected the susceptibility values. The susceptibility value decreased with increasing number of silica addition in nanocomposites; these results are in line and strengthen the magnetic properties test with VSM (Figure 4).

Table 3. The identification of value $\chi_{fd}$ (%) [29]

| Samples     | Classification | Interpretations                     |
|-------------|----------------|-------------------------------------|
| Fe$_3$O$_4$ (#S0) | $\chi_{fd}$ (%) | intermediate                       |
| #S1 (1:1)   | $\chi_{fd}$ (%) | intermediate                       |
| #S2 (1:2)   | $\chi_{fd}$ (%) | intermediate                       |
| #S3 (1:3)   | $\chi_{fd}$ (%) | intermediate                       |
| #S4 (3:1)   | $\chi_{fd}$ (%) | intermediate                       |

Furthermore, the measurement results of magnetic susceptibility values can also explain the grain size of a type of magnetic material. To find out about this, we must find the percentage value of the frequency-dependent susceptibility ($\chi_{fd}$ %). This can be seen from the comparison of the value of magnetic susceptibility at high and low frequencies. Tables 2 and 3 presented the results of the percentage value classification of frequency-dependent susceptibility ($\chi_{fd}$ %).

Table 3 showed the estimated magnetic susceptibility value on a high frequency($\chi_{hf}$) and low frequency ($\chi_{lf}$) on the superparamagnetic properties of Fe$_3$O$_4$/SiO$_2$. In sequenced with variations in the composition of constituent NPs, a linear relationship was obtained, namely the more addition of silica in the nanocomposites, the magnetic susceptibility value decreases. This occurs because silica is a non-magnetic material so that the greater the addition of silica in nanocomposites, then the magnetic properties of Fe$_3$O$_4$ will decrease [8,27]. The results are in accordance with the equation $\mathbf{M} = \chi \cdot \mathbf{H}$ with the obtained magnetic susceptibility value of $\chi$ $>$ 1, with $\chi_{fd}$ (%) which means that all samples belong to superparamagnetic (SP) with the particle size of <0.005 µm [28]. The magnetic susceptibility level ($\chi$) of a magnetic material has a linear correlation with magnetic intensity (H). In addition, magnetic intensity (H) and magnetization (M) also have a linear correlation with magnetic induction (B). Based on that, then the magnetic susceptibility value can be illustrated in a hysteresis curve (Figure 4).
Figure 5 explains the susceptibility magnitude at high and low frequencies for each sample with varied compositions of Fe₃O₄ and SiO₂. Based on the magnetic susceptibility value, Fe₃O₄/SiO₂ NCs with 1:1 composition has a magnetic susceptibility value of 0.0273 x 10⁻² m³/kg. From the identification, it was obtained the frequency-dependent susceptibility values $\chi_{fd}$ of 4.02% and 3.72% each for Fe₃O₄ NPs and Fe₃O₄/SiO₂ NCs sample (#S1), the lowest value compared from the sample #S2 (1:2), #S3 (1:3), and #S4 (3:1); for sample (#S4) Fe₃O₄ composition is more dominant from SiO₂ showed a higher susceptibility value ($\chi_{fd}$), even when compared to Fe₃O₄ NPs (sample #S0).

4. Conclusion
Fe₃O₄-NPs and Fe₃O₄/SiO₂-NCs materials have been synthesized from natural materials. PEG 4000 was able to be used as the media of composite formation with one-pot process technique, even though it did not affect Fe₃O₄ crystal structure/phase. However, the diffraction pattern was identified at the position (20°:18–23°). The existence of SiO₂ in the composite system (core-shell-like) has significantly decreased the magnetization of Fe₃O₄ NPs (~29 emu/g) and Fe₃O₄/SiO₂-NCs (~5 emu/g) as well as having superparamagnetic properties.

References
[1] Ghosh Chaudhuri R and Paria S 2012 Core/Shell Nanoparticles: Classes, Properties, Synthesis Mechanisms, Characterization, and Applications Chemical Reviews 112 2373–433
[2] Blaney L Magnetite (Fe₃O₄): Properties, Synthesis, and Applications 50
[3] Wu S, Sun A, Zhai F, Wang J, Xu W, Zhang Q and Volinsky A A 2011 Fe₃O₄ magnetic nanoparticles synthesis from tailings by ultrasonic chemical co-precipitation Materials Letters 65 1882–4
[4] Khalil M I 2015 Co-precipitation in aqueous solution synthesis of magnetite nanoparticles using iron(III) salts as precursors Arabian Journal of Chemistry 8 279–84
[5] Wei Y, Han B, Hu X, Lin Y, Wang X and Deng X 2012 Synthesis of Fe₃O₄ Nanoparticles and their Magnetic Properties Procedia Engineering 27 632–7

[6] Yew Y P, Shameli K, Miyake M, Ahmad Khairudin N B B, Mohamad S E B, Naiki T and Lee K X 2018 Green biosynthesis of superparamagnetic magnetite Fe₃O₄ nanoparticles and biomedical applications in targeted anticancer drug delivery system: A review Arabian Journal of Chemistry

[7] Al-Ruqeeshi M S, Mohiuddin T and Al-Saadi L K 2016 Green synthesis of iron oxide nanorods from deciduous Omani mango tree leaves for heavy oil viscosity treatment Arabian Journal of Chemistry

[8] Gao M, Li W, Dong J, Zhang Z and Yang B 2011 Synthesis of silica nanopowder Materials Science and Engineering 367 461–71

[9] Revia R A and Zhang M 2016 Magnetite nanoparticles for cancer diagnosis, treatment, and treatment monitoring: recent advances Materials Today 19 157–68

[10] Zelepukin I V, Shipunova V O, Mirkasymov A B, Nikitin P I, Nikitin M P and Deyev S M 2017 Synthesis and Characterization of Hybrid Core–Shell Fe₃O₄@SiO₂ Nanoparticles for Biomedical Applications Acta Naturae 9 58–65

[11] Zhang J, Zhai S, Li S, Xiao Z, Song Y, An Q and Tian G 2013 Pb(II) removal of Fe₃O₄@SiO₂–NH₂ core–shell nanomaterials prepared via a controllable sol–gel process Chemical Engineering Journal 215–216 461–71

[12] Hayes R, Ahmed A, Edge T and Zhang H 2014 Core–shell particles: Preparation, fundamentals and applications in high performance liquid chromatography Journal of Chromatography A 1357 36–52

[13] Gawande M B, Goswami A, Asefa T, Guo H, Biradar A V, Peng D L, Zboril R and Varma R S 2015 Core–shell nanoparticles: synthesis and applications in catalysis and electrocatalysis Chemical Society Reviews 44 7540–7590

[14] Cheng Y, Tan R, Wang W, Guo Y, Cui P and Song W 2010 Controllable synthesis and magnetic properties of Fe₃O₄ and Fe₃O₄@SiO₂ microspheres Journal of Materials Science 45 5347–52

[15] Anbarasu M, Anandan M, Chinnasamy E, Gopinath V and Balamurugan K 2015 Synthesis and characterization of polyethylene glycol (PEG) coated Fe₃O₄ nanoparticles by chemical co-precipitation method for biomedical applications Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 135 536–9

[16] Munasir, Dewanto A S, Kusumawati D H, Putri N P, Yulianingsih A, Sa’adah I K F, Taufiq A, Hidayat N, Sunaryono S and Supardi Z A 2018 Structure Analysis of Fe₃O₄@SiO₂ Core Shells Prepared from Amorphous and Crystalline SiO₂ Particles IOP Conference Series: Materials Science and Engineering 367 012010

[17] Munasir, Sultan A, Triwikantoro, Zainuri M and Darmiento 2013 Synthesis of silica nanopowder produced from Indonesian natural sand via alkali-fussion route International Conference on Theoretical and Applied Physics (LCTAP 2012) (Central of Kalimantan, Indonesia) pp 28–31

[18] Sonmez M, Georgescu M, Alexandrescu L, Gurau D, Ficai A and Andronescu D F and E 2015 Synthesis and Applications of Fe₃O₄@SiO₂ Core-Shell Materials Current Pharmaceutical Design

[19] Ahangaran F, Hassanzadeh A and Nouri S 2013 Surface modification of Fe₃O₄@SiO₂ microsphere by silane coupling agent International Nano Letters 3

[20] Larumbe S, Gómez-Polo C, Pérez-Landázabal J I and Pastor J M 2012 Effect of a SiO₂ coating on the magnetic properties of Fe₃O₄ nanoparticles Journal of Physics: Condensed Matter 24 266007

[21] Zhang L, Shao H, Zheng H, Lin T and Guo Z 2016 Synthesis and characterization of Fe₃O₄@SiO₂ magnetic composite nanoparticles by a one-pot process International Journal of Minerals, Metallurgy, and Materials 23 1112–8
[22] Jal P K, Sudarshan M, Saha A, Patel S and Mishra B K 2004 Synthesis and characterization of nanosilica prepared by precipitation method Colloids and Surfaces A: Physicochemical and Engineering Aspects 240 173–8

[23] Jian G, Liu Y, He X, Chen L and Zhang Y 2012 Click chemistry: a new facile and efficient strategy for the preparation of Fe3O4 nanoparticles covalently functionalized with IDA-Cu and their application in the depletion of abundant protein in blood samples Nanoscale 4 6336

[24] Munasir, Dewanto A S, Yulianingsih A, Saadah I K F, Supardi Z A I, Mufid A and Taufiq A 2017 Composites of Fe3O4@SiO2 from Natural Material Synthesized by Co-Precipitation Method IOP Conference Series: Materials Science and Engineering 202 012057

[25] Morrow B A and McFarlan A J 1992 Surface vibrational modes of silanol groups on silica The Journal of Physical Chemistry 96 1395–400

[26] Yew Y P, Shameli K, Miyake M, Kuwano N, Bt Ahmad Khairudin N B, Bt Mohamad S E and Lee K X 2016 Green Synthesis of Magnetite (Fe3O4) Nanoparticles Using Seaweed (Kappaphycus alvarezii) Extract Nanoscale Research Letters 11

[27] Zemtsova E G, Ponomareva A N, Panchuk V V, Galiullina L F and Smirnov V M Structures For Targeted Drug Delivery 9

[28] Kulkarni S A, Sawadh P S and Palei P K 2014 Synthesis and Characterization of Superparamagnetic Fe3O4@SiO2 Nanoparticles Journal of the Korean Chemical Society 58 100–4

[29] Abboud M, Youssef S, Podlecki J, Habchi R, Germanos G and Foucaran A 2015 Superparamagnetic Fe3O4 nanoparticles, synthesis and surface modification Materials Science in Semiconductor Processing 39 641–8

[30] C W Chem 1977 Magnetism and Metallurgy of Soft Magnetic Materials Imprint: North Holland

[31] James R D 2015 Materials science: Magnetic alloys break the rules Nature 521 298–9

[32] Dearing J A 1994 Environmental Magnetic Susceptibility: Using the Bartington MS2 System (Kenilworth: Chi Publishing)

Acknowledgements

We would like to thank the Indonesian Ministry of Research, Technology and Higher Education through the Penelitian Terapan Unggulan Perguruan Tinggi (PTUPT) program for providing the financial support in this research and its publication.