The Correlation Analysis of Magnetic Susceptibility and Elemental Composition of Very Fine Sand from Anoi Itam Beach in Weh Island, Aceh

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Abstract. Ironsand deposits might contain Fe as well as other valuable elements and minerals that could be used in a variety of applications. Often, high Fe content deposits are preferable for exploration. An earlier study shows that the highest Fe content is found in the very fine sand (VFS) size. In this study, seven VFS samples from Anoi Itam were subjected to magnetic measurements as well as X-Ray florescence (XRF), X-Ray diffraction (XRD), and correlation analyses to investigate further characteristics and how magnetic susceptibility correlates with the elemental composition of ironsand. Magnetic susceptibility varies from $2207.77 \times 10^{-8}$ m$^3$ kg$^{-1}$ to $4476.68 \times 10^{-8}$ m$^3$ kg$^{-1}$. The main elements contained in the sample are Fe, Ti, Si, and Al. Meanwhile, other elements have small concentrations (<2%). Based on XRD analyses, magnetite and ilmenite are the main minerals with varying concentrations in each sample. The correlation analysis shows that magnetic susceptibility has a weak correlation with Fe probably because Fe forms minerals with very different magnetism, namely magnetite and ilmenite.

1. Introduction
Indonesia has abundant natural resources as a result of volcanic eruptions, one of which is ironsand. Ironsand contains valuable Fe and mineral that can be utilized for various applications. This matter has caused many parties to carry out mining activities. Therefore, the mining process must be selective to obtain potential ironsand. To find out the distribution of ironsand characteristics, research is needed in various regions. Research on ironsand has been carried out, one of which is in Aceh Province [1,2]. Previous studies have shown that the highest Fe content was found in Very Fine Sand (VFS) grain size [3]. In this paper, VFS samples from Anoi Itam Beach become research subjects using the integration of magnetic susceptibility methods, X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and rank Spearman correlation analysis to determine the characteristics and correlation between magnetic susceptibility and elemental composition.

2. Geological Setting
Anoi Itam Beach is located in Gampong Anoi Itam, Sukajaya District, Sabang City, Weh Island, Aceh. This beach is located at the coordinates 5°50'15.0" N and 95°22'26.8" E. One of the mountains on Weh Island is Mount Jaboi. Mount Jaboi is a type C volcano and the only mountain that still shows volcanic activity to date on Weh Island. The rocks that make up Weh Island are shown in Figure 1, which consists...
of Alluvium (Qh) and Weh Island Volcano Rocks (QTvw). The alluvium consists of gravel, sand, and mud which is the result of the scraps of various old and young rocks with silt to crust sizes that are deposited on plains such as river estuaries and beaches. Weh Island Volcano Rock (QTvw) is the bedrock that forms Weh Island which consists of andesite-basalt, tuff, and agglomerates. This unit is generally dark gray to blackish. Besides, tuffaceous sandstones are exposed in the Anoi Itam area with a graded bedding structure, coarsely grained to fine, and are thought to be Miocene in age.

![Geological map of Weh Island](image)

**Figure 1.** Geological map of the study area (modified from [4]).

### 3. Experimental Methods

Seven points taken with codes SA-01, SA-02, SA-03, SA-04, SA-05, SA-06, and SA-07 is shown in Figure 2. Ironsand was prepared by sieving at 120 mesh size to get VFS grain. Then, each point was inserted into three holders. Twenty-one samples of VFS ironsand tested for frequency-based magnetic susceptibility using a Bartington MS2 susceptibility meter with two different frequencies, namely 0.46 kHz for low frequencies ($\chi_{lf}$) and 4.6 kHz for high frequencies ($\chi_{hf}$). Seven samples with the most representative magnetic susceptibility values at each point were smoothed using a pestle and mortar and then sieved with a size of 230 mesh for XRF and XRD testing. X-Ray Fluorescence is measured using Supermini 200 X-Ray Fluorescence to determine the elemental and mineral oxide content. X-Ray Diffraction is measured using SmartLab X-Ray Diffraction to determine the mineral content contained in the sample. Furthermore, the Spearman rank correlation analysis was carried out to determine the correlation between element composition and magnetic susceptibility with reference values divided into five parts [5].
4. Results and Discussion

4.1. Magnetic Susceptibility and Element Composition Characteristics

Based on Table 1, the mean value of $\chi_{lf}$ varies between $2207.77 \times 10^{-8} \text{m}^3\text{kg}^{-1}$ to $4476.68 \times 10^{-8} \text{m}^3\text{kg}^{-1}$ with $\chi_{fd}$% values ranging from 6.65% to 9.57% that indicates VFS iron sand samples have a mixture of superparamagnetic (SP) grain content and not SP [6]. Besides, based on XRF results, the VFS iron sand sample contains the main elements, namely Fe, Ti, Si, and Al as well as the mineral oxide content of them. Other oxide minerals and elements contain small concentrations (<2%). Meanwhile, XRD testing showed that the minerals contained in the samples were quite diverse, with the main minerals being magnetite and ilmenite.

| Codes  | Average $\chi_{lf}$ ($10^{-8} \text{m}^3\text{kg}^{-1}$) | Average $\chi_{hf}$ ($10^{-8} \text{m}^3\text{kg}^{-1}$) | Average $\chi_{fd}$% |
|--------|--------------------------------------------------|--------------------------------------------------|------------------|
| SA-01  | 3648.80                                          | 3360.21                                          | 7.90             |
| SA-02  | 3974.35                                          | 3708.90                                          | 6.65             |
| SA-03  | 2207.77                                          | 2037.50                                          | 7.74             |
| SA-04  | 3949.91                                          | 3669.10                                          | 7.16             |
| SA-05  | 2757.55                                          | 2561.47                                          | 7.06             |
| SA-06  | 4056.85                                          | 3663.92                                          | 9.57             |
| SA-07  | 4476.68                                          | 4125.00                                          | 7.86             |

From Table 1, it can be seen that from point SA-01 to SA-07, average $\chi_{lf}$ value tends to be an increase. However, there is a decrease in points SA-03 and SA-05. The low $\chi_{lf}$ values found at points SA-03 and SA-05 were possible due to the different magnetic minerals in the samples. When associated with XRD results, SA-03-1 contains several diamagnetic minerals such as quartz, dolomite, and rutile. Meanwhile, the SA-05-3 sample contained diamagnetic minerals, namely berlinite and alinite. Previous studies have shown that the presence of berlinite minerals causes a decrease in the susceptibility of Fine Sand (FS) iron sand during an increasing trend of magnetic susceptibility along with decreasing grain size of iron sand [3]. Mineral magnetism level also depends on the amount of Fe contained in it. Sample SA-01-3 has a lower magnetic susceptibility value because the magnetite formula contains less Fe than
other samples. This matter indicates that the magnetite contained in the SA-01 is not magnetic enough than the magnetite contained in the other sample points.

4.2. Ironsand Source

The present elements may come from the same source, namely from weathering and the release of minerals by volcanic rock fragments. Besides, the high Fe content in iron sand samples can be caused by the mafic source rock [7]. The mafic source can be determined from the \( \frac{Al_2O_3}{TiO_2} \) ratio with a low value (<14) [8]. The \( \frac{Al_2O_3}{TiO_2} \) result calculation shows an average value of 0.72, which indicates the source rock of iron sand is mafic. When viewed from the XRD test results, the types of magnetic minerals contained in each sample have various types of magnetic minerals. Most of the minerals found in iron sand such as berlinite, coesite, sphalerite, rutile, alinite, dolomite, albite, and anorthite are minerals in hydrothermal veins or contact metamorphism. The formation of albite and berlinite minerals in the sample suggests that the area where iron sand was formed is a rock containing an andesite-basalt composition [9]. This matter suggests that the minerals contained in VFS iron sand at Anoi Itam Beach probably was formed from the metamorphism of the mafic andesite-basalt hydrothermal veins due to contact with high temperatures in the Jaboi geothermal system.

Figure 3 is a plot between the \( \chi_{lf} \) and \( \chi_{fd} \) values from the VFS sample. The magnetic susceptibility of iron sand samples from volcanic rocks will usually increase as the frequency-dependent magnetic susceptibility \( \chi_{fd} \) increases [10]. Meanwhile, for polluted samples, the value of \( \chi_{fd} \) will decrease as \( \chi_{lf} \) increases. Besides, the \( \chi_{fd}\% \) result obtained also shows that the magnetic minerals were derived from pedogenesis. This matter is because magnetic minerals derived from pedogenesis have high \( \chi_{fd}\% \) values, whereas lower \( \chi_{fd}\% \) values (<4%) found in contaminated samples or anthropogenic sources [11]. This matter is consistent with the results of other studies that show that the magnetic minerals in iron sand samples from the Cirebon coast are of anthropogenic origin that is indicated by a low value (<2%) [12].

![Figure 3. Plot the \( \chi_{lf} \) value against \( \chi_{fd} \) from the VFS samples.](image)

4.3. Correlation Analysis between Elemental Composition and Magnetic Susceptibility Value

The correlation coefficient between element composition and magnetic susceptibility values is shown in Table 2. The presence of Ti in the form of rutile minerals causes Ti to have a negative correlation with magnetic susceptibility. Although Ti is also present in ilmenite, the contribution of Fe is more dominant to magnetic susceptibility because the magnetic moment of Fe is higher than Ti [13-14]. Meanwhile, Al is in the minerals anorthite and albite, Ca is in the form of anorthite, dolomite, and alinite, and Mg is in the form of dolomite. Even though it is in the mineral magnetite, the presence of Mg only acts as an impurity element with very little concentration. All of these minerals are diamagnetic minerals. This matter is probably why the element has a weak correlation with magnetic susceptibility.
Besides, most rock-forming minerals that do not contain Fe are diamagnetic. Therefore, in general, the minerals sphalerite, quartz, berlinite, and alinite are diamagnetic. Diamagnetic materials have small magnetic susceptibility values so that Zn, S, Si, P, and Cl have a weak to moderate correlation with magnetic susceptibility.

Table 2. The correlation coefficient between magnetic susceptibility and elemental composition.

| Element | Magnetic Susceptibility |
|---------|------------------------|
| Mg      | 0.07                   |
| Al      | -0.16                  |
| Si      | -0.32                  |
| P       | 0.32                   |
| S       | 0.49                   |
| Cl      | 0.57                   |
| K       | -0.46                  |
| Ca      | 0.07                   |
| Ti      | -0.07                  |
| Mn      | 0.61                   |
| Fe      | 0.32                   |
| Zn      | -0.39                  |
| Zr      | 0.14                   |
| V       | -0.14                  |

Other elements that appeared during XRF measurements, such as K, Zr, and V, were not identified during XRD measurements. This matter is probably because these elements form minerals with very little concentration. Because it is insensitive to minerals with small concentrations (<4%), XRD is unable to identify these minerals [15]. The correlation analysis results show that their correlation is mostly very weak, so that the minerals formed may be diamagnetic minerals.

Magnetic susceptibility correlates strongly with Mn and weakly with Fe. This matter happens because Fe is in a mineral form that has different magnetic properties. Fe in the form of magnetite will be ferrimagnetic while in the form of ilmenite, it will be paramagnetic. This is probably the reason Fe has a weak correlation with magnetic susceptibility. Previous studies have found that the two samples studied showed negative magnetic susceptibility values even though some paramagnetic materials were at low concentrations [16]. It can be assumed that even though there are ferrimagnetic minerals, the magnetic susceptibility may decrease due to the presence of paramagnetic and diamagnetic minerals which are more dominant.

Mn is an antiferromagnetic metal that can sufficiently influence magnetic susceptibility although it is not as strong as Fe [13,17]. The presence of Mn makes a positive contribution to MnO susceptibility leading to a strong positive correlation between Mn and magnetic susceptibility. Besides, Mn can bind with Fe to form a mineral. Because it has the largest magnetic moment of the transition metal group, the combination of Mn and Fe in one mineral makes a positive contribution to magnetic susceptibility. However, the presence of these minerals is possible in small amounts so that they do not appear in XRD measurements.

5. Conclusion
The VFS ironsand sample at Anoi Itam Beach is classified as magnetic, which is characterized by a high susceptibility value with a mixture of SP and non-SP domains. Based on XRF and XRD testing, VFS ironsand samples have quite diverse concentrations of elements and types of minerals with the largest Fe content and contain the main minerals magnetite and ilmenite. The high Fe content does not always result in high magnetic susceptibility values. This matter is possible due to the presence of paramagnetic and diamagnetic minerals in the sample. Besides, the magnetic minerals were derived from pedogenesis with andesite-basalt source rocks originating from Mount Jaboi. Based on correlation analysis, the weak
correlation between element content and magnetic susceptibility is because these elements are in diamagnetic minerals. Meanwhile, a weak correlation between Fe and magnetic susceptibility because Fe forms minerals with very different magnetism, namely magnetite and ilmenite.

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