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D. Fitriani
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Method in estimating mass-specific magnetic susceptibility of strongly magnetic or low quantity substances

D. Fitriani[1,2*], L. O. Safiuddin[1], K. Kodama[3], S. Bijaksana[4]

[1] Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia
[2] Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, JL. Raya Bandung-Sumedang KM 21, Sumedang 45363, Indonesia
[3] Center for Advanced Marine Core Research, Kochi University, Kochi 783-8502, Japan
[4] Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia
*Corresponding author, E-mail: dini.fitriani@phys.unpad.ac.id

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Abstract. Magnetic susceptibility meters have certain measuring range and standard-size samples. For measuring strongly magnetic substances, it could exceed sensor range while low quantity substances might not be placed correctly in sensor causing error. A frequently used method for measuring such substances is by measuring a reduced volume of substances placed in the center of sensor. In this study, we tested the accuracy of typical magnetic susceptibility meter (a Bartington MS2B magnetic susceptibility meter) against reduced sample volume and found that placing the reduced volume of samples even in the center of sensor still produced significant error. We moved on to propose a new method in measuring substances that are too strongly magnetic or too low in quantity by combining such substances with other substances whose magnetic susceptibility are known. The method was tested in variety of substances ranging from industrial samples to particulates of vehicle exhaust. Measurement of combinations between tested and reference substances in various proportions lead to an estimation of mass-specific magnetic susceptibility of tested substance through graphical analyses. Compared to measuring reduced volume of sample, we found that the proposed method provides better estimate of the true mass-specific magnetic susceptibility.

Keywords: *Magnetic susceptibility meter, reduced sample volume, combining susceptibility method*

1 Introduction

In recent years, rock magnetic methods have been used widely in a wide range of applications, including in environmental pollution studies (Muxworthy *et al*., 2003; Spiteri *et al*., 2005; Chaparro *et al*., 2008; Maher *et al*., 2008; Bijaksana and Huliselan, 2010), reconstruction of past climates (Geiss *et al*., 2008; Xie *et al*., 2009; Franco *et al*.,2012), paleointensity of the Earth's magnetic field (Brachfeld and Banerjee, 2000; Yokoyama *et al*., 2007; Irurzun *et al*., 2009), archeology (Mooney *et al*., 2003; Rada *et al*., 2008) and biomagnetism (Torres de Araujo *et al*., 1986; Moskowitz *et al*., 2008; Li *et al*., 2010). There are scores of magnetic parameters used in rock magnetic studies, but the most common one is the low-field magnetic susceptibility, which generally reflects the characteristic and intensity of response of magnetized material to the external field (Petrovsky, 2007). In many studies, the objective of measuring low-field magnetic susceptibility or simply the magnetic susceptibility is to quantify the amount of magnetic minerals in the measured sample (Lecoanet *et al*., 1999). Measurement of this parameter is favored as it is relatively rapid, cost effective and non-destructive.

There are several instruments to measure magnetic susceptibility for rock and environmental materials; the most common one is the Bartington MS2 magnetic susceptibility system (Bartington Instruments Ltd, Oxford, England). Although measurements could also be made on rock surfaces and cores, the most common measuring method is the measurement of standard-sized samples of 10 to 12 cm^3 in size that could be either cylindrical or cubical in shape. The Bartington MS2B sensor has the measuring range of 1 to 9999 x 10^{-5} SI (1 to 9999 x 10^{-6} cgs) if used in volume-specific susceptibility (Bartington Instruments Ltd, 2010). With such design, samples that are much less than 10 cm^3 in volume might not be placed correctly within the sensor causing significant error. Studying the sizes and volume errors of sample that is much less than 10 cm^3, Dearing (1999) found that as sample's volume becomes smaller the underestimate of true magnetic susceptibility increases. This might caused certain difficulties in studies in which the samples are either too low in quantity (such as studies of vehicle-derived particulates or dust-loaded tree leaves) or magnetically too strong. Certain natural samples, such as the extrusive mafic igneous rocks from South-Central Alaska have susceptibility value of about 13900 x 10^{-6} cgs (Sanger *et al*., 2003) which is greater than the measuring range of the Bartington MS2B sensor. (Note that Bartington has released a new device termed MS2G that could measure small quantity homogenous sample of ~ 1 cm^3. The device, however, has similar measuring range as it is connected to MS2 system).

So far, the most common and, apparently, the logical method of measuring substances that are either too low in quantity or magnetically too strong is placing a small amount of substance (< 10 cm^3 in volume) preferably in the center of measuring space. In this study, we tested the accuracy of such approach by designing a set of internal sample holders that could accommodate various amount of substance in the center MS2B sensor of a Bartington MS2 magnetic susceptibility system. We found that such approach still produces error in its magnetic susceptibility. Such finding inspired us to propose a new method in measuring substances that are either too low in quantity or magnetically too strong. In the proposed method, tested substance is combined with control substance whose magnetic susceptibility is known. This method is tested in variety of samples ranging from low quantity substances, such as magnetic particulates from vehicle emission, to strongly magnetic substances, such as industrial grade iron pigments.

2 Testing the accuracy of placing reduced sample volume in the center of measuring space

Like many instruments in rock magnetism or paleomagnetism, the Bartington MS2 magnetic susceptibility system with its MS2B sensor, uses a standard cylindrical sample holder that is 25.4 mm in diameter and 22 mm in height. To test the accuracy of placing reduced sample volume in the center of the MS2B sensor, we designed a set of internal sample holders that can be placed inside the standard sample holder. With their small diameters ranging from 3 to 18 mm, these internal sample holders could accommodate small amounts of sample. Figure 1 shows the standard sample holder, example of internal sample holder, and the combined standard and internal sample holders. Three industrial magnetic substances, namely YO-8087 (labeled as yellow oxide), R-9998 (labeled as pure red iron oxide) and MO-4232 (labeled as magnetic oxide), were used as tested substances. Figure 2 shows the XRD profiles of these substances showing that YO-8087 is goethite (FeO-OH), R-9998 is hematite (α-Fe_2O_3), and MO-4232 is magnetite (Fe_3O_4). All the above are industrial substances in powder forms and were manufactured by Pfizer (Minerals, Pigments & Metals Division, New York, USA).

First, we measured the volume-specific magnetic susceptibility, denoted as κ, for the fully-filled standard samples of these three substances using the Bartington MS2 magnetic susceptibility system with its MS2B sensor. The sensor can be used in two frequencies (0.47 kHz and 4.7 kHz), but in this study only the low frequency of 0.47 kHz was used. Mass-specific magnetic susceptibility, χ, was obtained by converting the measured volume-specific magnetic susceptibility and the mass of the samples measured using an Ohaus analytical scale type Explorer®. Subsequently, we repeat the measurements by filling up the internal sample holders starting from the smallest one (3 mm diameter) to the largest one (18 mm diameter) and measured their volume-specific magnetic susceptibility. The measurements were carried out in five sets of sample for each diameter. The

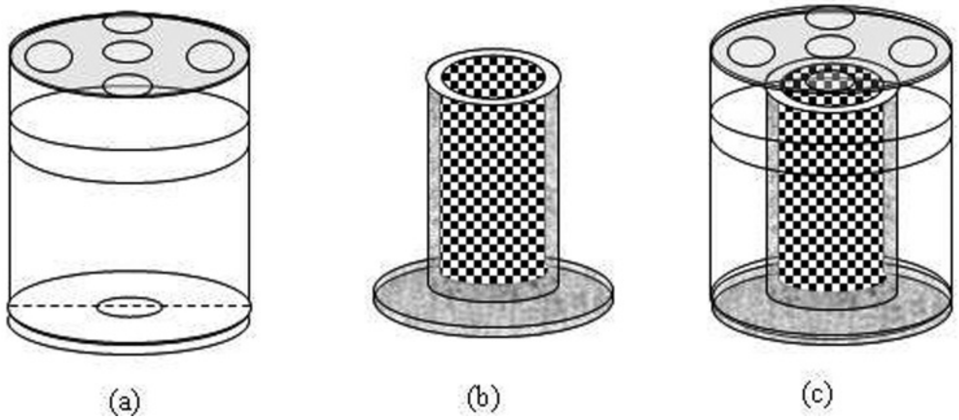

Figure 1. (a) Standard sample holder. (b) Internal sample holder with the samples. (c) Combined standard and internal sample holders.

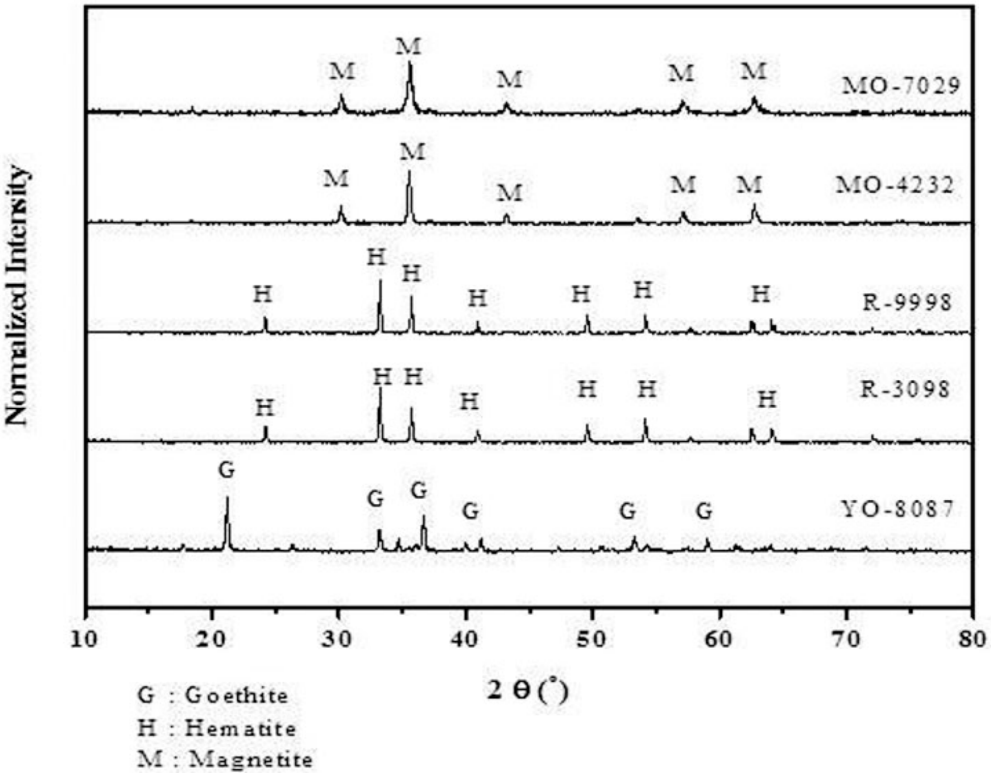

Figure 2. XRD analyses of industrial substances.

average results and the standard error of the measurements are given in Table 1 which shows that the mass-specific magnetic susceptibility for smaller sample size (*i.e.*, those measured using internal sample holders) differs from that measured for fully-filled samples. Substance R-9998 shows that the mass-specific magnetic susceptibility increases with diameter of internal sample holder. Except for the smallest diameter, similar observation was also found in substances YO-8087 and MO-4232. Substance MO-4232 is very strong so that the magnetic susceptibility of fully-filled standard samples could not be determined by using Bartington MS2B as it exceeds 9999 x 10^{-5} SI. In order to have reference value of MO-4232, we used a new instrument developed by Kodama (2010). At frequency of 500 Hz, the mass-specific magnetic susceptibility of fully-filled standard of MO-4232 is 25110 x 10^{-8} m^3/kg.

The above results show that magnetic susceptibility measurement using smaller volume of sample, a practice that is common when measuring substances that are either magnetically too strong or very low in quantity, produces error whose extent depends on the overall sample volume. Smaller sample produces greater error. It is apparent that, the sensing coils in the magnetic susceptibility meter respond properly to the standard size sample. The respond deteriorates as the sample size gets smaller even though the sample is placed in the center of the measuring space.

		YO-8087		R-9998		MO-4232	
	Diameter (mm)	Mass (g)	χ ($\times 10^{-8}$ m^3/kg)	Mass (g)	χ ($\times 10^{-8}$ m^3/kg)	Mass (g)	χ ($\times 10^{-8}$ m^3/kg)
Standard sample holder	25.4	3.6767	120.8	7.5048	4511.2	4.0999	25110±56.67*
Incremental internal sample holder	3	0.0827	132.1±0.2	0.1600	4218.6±10.1	0.0701	24063.2±146.6
	6	0.3115	114.7±0.5	0.6200	4290.9±9.9	0.3300	24115.5±43.5
	9	0.7106	115.3±0.6	1.4233	4316.5±2.5	0.7164	24234.6±18.3
	12	1.2619	115.8±0.4	2.5306	4324.1±6.1	1.2530	24254.2±21.7
	15	1.9596	117.0±0.1	3.9467	4366.6±4.7	1.9905	24282.8±5.2
	18	2.8339	120.4±0.2	5.6856	4471.9±3.4	3.0235	24593.7±4.9

*Magnetic susceptibility was measured using a new instrument developed by Kodama (2010) at frequency of 500 Hz.

Table 1. Mass-specific susceptibility of YO-8087, R-9998 and MO-4232 as function of quantity of substances.

3 Combining susceptibility method

Natural sample usually contain more than one magnetic mineral. In theory, as discussed in Dearing (1999) magnetic susceptibility of a sample which contains mixtures of minerals can be estimated in terms of the sum of the magnetic susceptibility values of the individual minerals. Consider a case, where there are several magnetic minerals in a sample, each with its own distinct magnetic properties. Thus, the volume-specific magnetic susceptibility of the sample, κ, is simply given by the following equation

$$\kappa = \sum_i \kappa_i F_i \qquad (1),$$

where κ_i is the volume-specific magnetic susceptibility value of the *i*-th component and F_i is the volume fraction of the *i*-th component. Using $\kappa = \chi\rho$, where ρ is the total density of the sample, equation (1) could be converted into the following equation

$$\chi = \sum_i \chi_i f_i \qquad (2),$$

where χ_i is the calculated mass-specific magnetic susceptibility value of the *i*-th component and f_i is the mass fraction of the *i*-th component.

If there are only two different substances in the sample, then χ is simply given by

$$\chi = \chi_1 f_1 + \chi_2 f_2 \quad (3),$$

where χ_1 and χ_2 are respectively the mass-specific magnetic susceptibility of the first and second substances, while f_1 and f_2 are respectively their fractions. Since the total fractions is equal to one ($f_1 + f_2 = 1$), equation (3) could rewritten as

$$\chi = (\chi_1 - \chi_2) f_1 + \chi_2 \quad (4),$$

The above equation (4) is the base of the proposed combining susceptibility method. With this equation, it is then possible to estimate the mass-specific magnetic susceptibility of the first or tested substance (χ_1) that either magnetically too strong or too low in quantity by plotting mass-specific magnetic susceptibility of the sample versus its mass fraction (χ versus f_1). This can be accomplished by combining the first substance of varying quantity with the matrices of second substance or reference substance whose mass-specific magnetic susceptibility (χ_2) is known, preferably one that is much less magnetic than the tested substance. Measuring volume-specific magnetic susceptibility of such samples with a magnetic susceptibility meter and then calculating their mass-specific susceptibility, one could plot χ versus f_1. The slope of such plot provides the value of χ_1 minus χ_2 while the intercept should be equal to χ_2. Since χ_2 is known, then the intercept which theoretically equals to χ_2 could be used as a factor to validate the estimated value of χ_1.

To test the effectiveness of the proposed combining susceptibility method, we used variety of substances as ranging from industrial substances, lateritic soils, particulates from vehicle exhaust to common substances, such as plasticine and common wheat flour. Industrial samples were chosen as they were homogenous in size as well as in composition. Apart from the three industrial substances mentioned earlier (YO-8087, R-9998, and MO-4232), two other substances namely R-3098 (labeled as pure red iron oxide) and MO-7029 (also labeled as magnetic oxide) were also used in the experiment. XRD analyses show that R-3098 is hematite while MO-7029 is magnetite (see Fig. 2). Both R-3098 and MO-7029 were also in powder forms and manufactured by Pfizer.

The lateritic soil is used in this experiment to represent real natural substance where the magnetic mineralogy and granulometry are not necessarily homogenous. Thus, the magnetic composition and magnetic grains sizes in the small amount of sample might differ from that in the large sample. This type of soil is rich in iron and aluminum and generally has high magnetic susceptibility. Soil samples were obtained from a nickel mine in Pomalaa, Southeast Sulawesi, Indonesia. Detailed rock magnetic studies on these soil samples were described by Safiuddin *et al.* (2011). Vehicle-derived particulates were used as tested substances as they represent substances that could be obtained only in low quantity. Earlier study by Lu *et al.* (2005) and Marie *et al.* (2010) showed the presence of magnetic particles in the vehicle-derived particulates. Vehicle-derived particulates might also less homogeneous in composition compared to industrial magnetic substances. Therefore, in such heterogeneous substance, a particular quantity or part might differ in composition with other quantities or parts. Vehicle-derived particulates in this experiment were collected from the exhaust pipe of buses using plastic scraper. In this experiment, non magnetic plasticine and common wheat flour were used as second or reference substances. For all substances, standard mass-specific magnetic susceptibility was determined by measuring samples of fully-filled substance in standard size sample holder. The results are listed in Table 2. Magnetic susceptibilities of MO-4232 and MO-7029 were measured by a new instrument developed by Kodama (2010) at frequency of 500 Hz.

Substance	Standard mass-specific magnetic susceptibility ($\times 10^{-8}$ m^3/kg)
YO-8087	120.79
MO-4232	25110*
MO-7029	30629*
R-3098	82.06
R-9998	4511.20
Lateritic soils	3011.24
Vehicle-derived particulates	106.61
Plasticine	15.95
Common wheat flour	1.82

*Magnetic susceptibility was measured using a new instrument developed by Kodama (2010) at frequency of 500 Hz.

Table 2. List of the substances used in this study and their standard mass-specific magnetic susceptibility. The standard magnetic susceptibilities of MO-4232 and MO-7029 were measured by a new instrument developed by Kodama (2010).

In the first set of experiment, we tested the proposed method on moderately magnetic samples. YO-8087 and R-3098 were used as tested substances while plasticine was used as reference substance. Five different quantities of tested substances were weighted and then placed inside small capsules, which were later placed in the centre of standard sample holder surrounded by matrices of plasticine as reference substances (see Fig. 3). In combination 1 (YO-8087 and plasticine), the quantity of YO-8087 varies from 21.6 to 107.4 mg that is equal to mass fraction of 0.32 to 1.55%. In combination 2 (R-3098 and plasticine), the quantity of R-3098 varies from 24.7 to 125 mg that is equal to mass fraction of 0.36 to 1.80%. All mass measurements were conducted using an Ohaus Explorer® analytical balance. We assume that there was no error in the measurement of samples' mass and volume as well as in the determination of mass fraction. All samples were then measured for volume-specific magnetic susceptibility using a Bartington MS2B magnetic susceptibility meter. Five readings were taken for each sample. The measured volume-specific magnetic susceptibility was then converted into the mass-specific magnetic susceptibility using the expression $\chi = \kappa / \rho$.

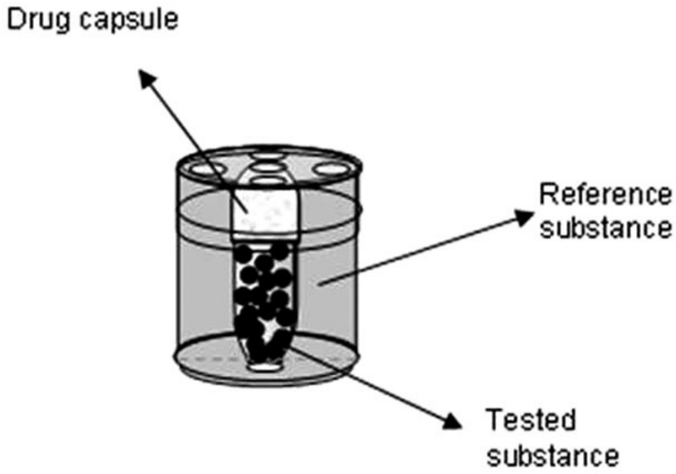

Figure 3. Tested substance surrounded by reference substance placed into standard sample holder in the combining method.

In the second set of experiment, we tested the proposed method on strongly magnetic samples. MO-4232 and MO-7029 were used as tested substances while plasticine and R-9998 were used reference substances. In combination 3 (MO-4232 and plasticine) and combination 4 (MO-4232 and R-9998), the quantity of MO-4232 varies from 29.2 to 150.7 mg. In terms of mass fractions, these amounts of MO-4232 are 0.43 to 2.16% for combination 3 and 0.40 to 2.05% for combination 4. Meanwhile, in combination 5 (MO-7029 and plasticine) and combination 6 (MO-7029 and R-9998), the quantity of MO-7029 varies from 5.68 to 287.8 mg. In terms of mass fractions, these amounts of MO-7029 are 0.83 to 4.05% for combination 5 and 0.79 to 3.85% for combination 6. The methodology of measurement for this second set of experiment is the same to that of the first experiments.

The experiment was then repeated in the third set of experiment as we tested the proposed method on lateritic soil samples that represent natural substances. Soil samples were used in combination with YO-8087 as reference substance (combination 7). The quantity of soil samples in the five samples of combination 7 varies from 50.0 to 249.6 mg. These amounts of soil sample translate into 1.41 to 6.65% of mass fraction.

Lastly, the experiment was repeated in the fourth set of experiments as we tested the proposed method on vehicle-derived particulates for that represent low quantity substances. Vehicle-derived particulates were combined with plasticine to form combination 8 and with common wheat flour to form combination 9. The quantity of vehicle-derived particulates varies from 2.9 to 16 mg. In terms of mass fractions, these amounts of the particulates are 0.04 to 0.23% for combination 8 and 0.06 to 0.32% for combination 9.

4 Results and Discussions

Figure 4 shows the results of the first set of experiments where YO-8087 and R-3098 were combined with plasticine as combination 1 and combination 2. The plotting of χ versus f_1 shows that there are strong correlations between the mass-specific susceptibility and mass fraction of tested substance as indicated by the values of r^2 (square of correlation coefficient) exceeding 0.99. For both combinations 1 and 2, the intercept values of 16.21 and 16.39 x 10^{-8} m^3/kg are very close to the standard mass-specific susceptibility of plasticine (listed as 15.95 x 10^{-8} m^3/kg in Table 2). In accordance to equation (4), the slopes of these best fit lines are simply the estimated mass-specific magnetic susceptibility of tested substance minus that of reference substance ($\chi_1 - \chi_2$). Thus, the estimated mass-specific magnetic susceptibilities of YO-8087 and RO-3098 are, subsequently, 118.46 x 10^{-8} m^3/kg and 81.26 x 10^{-8} m^3/kg. These are very close with the values of standard mass-specific magnetic susceptibilities of 120.79 x 10^{-8} m^3/kg and 82.06 x 10^{-8} m^3/kg listed in Table 2.

Figure 5 shows the results of the second set of experiments where strongly magnetic MO-4232 and MO-7029 were combined with plasticine (Figure 5a) and R-9998 (Figure 5b). As shown in Figure 5a, despite the strong correlations between χ and f_1 as indicated by the values of r^2 (square of correlation coefficient) exceeding 0.99, the intercept values are lower than expected giving only 12.07 x 10^{-8} m^3/kg for combination 3 (MO-4232 and plasticine) and – 53.35 x 10^{-8} m^3/kg for combination 5 (MO-7029 and plasticine). In contrast, shown in Figure 5b, stronger correlations between χ and f_1 and better values of intercept were observed when magnetically stronger reference substance (R-9998) was used replacing magnetically weaker reference substance (plasticine). For both combinations 4 and 6, the intercept values of 4402.81 x 10^{-8} m^3/kg and 4408.35 x 10^{-8} m^3/kg are close to the standard mass-specific susceptibility of R-9998 (listed as 4511.20 x 10^{-8} m^3/kg in Table 2). Thus, the estimated mass-specific magnetic susceptibilities of MO-4232 and MO-7029 are, subsequently, 25854.20 x 10^{-8} m^3/kg and 32198.82 x 10^{-8} m^3/kg. Apparently, when used on strongly magnetic substances, the accuracy of the proposed method depends heavily on the magnetic strength of the reference substance. Magnetically stronger reference substance provides better estimates for the tested substances compared to magnetically weak reference substance.

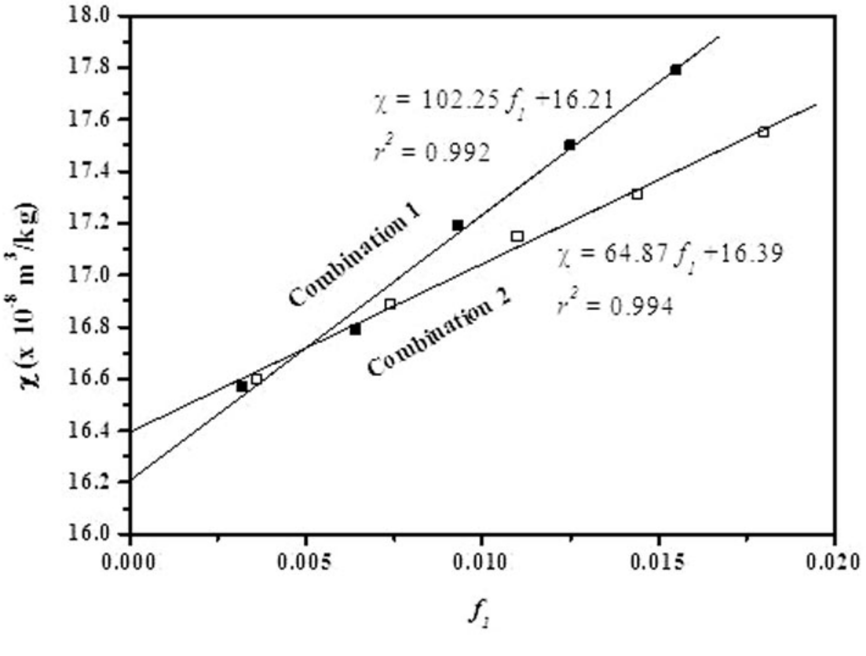

Figure 4. Plots χ versus the fraction of tested substance f_1 in the experiments where YO-8087 (solid diamonds) and R-3098 (hollow squares), were combined with plasticine as reference substance (combinations 1 and 2, respectively). Parameters of best fit lines as well as, r^2 (the square of correlation coefficient) were given next to each line.

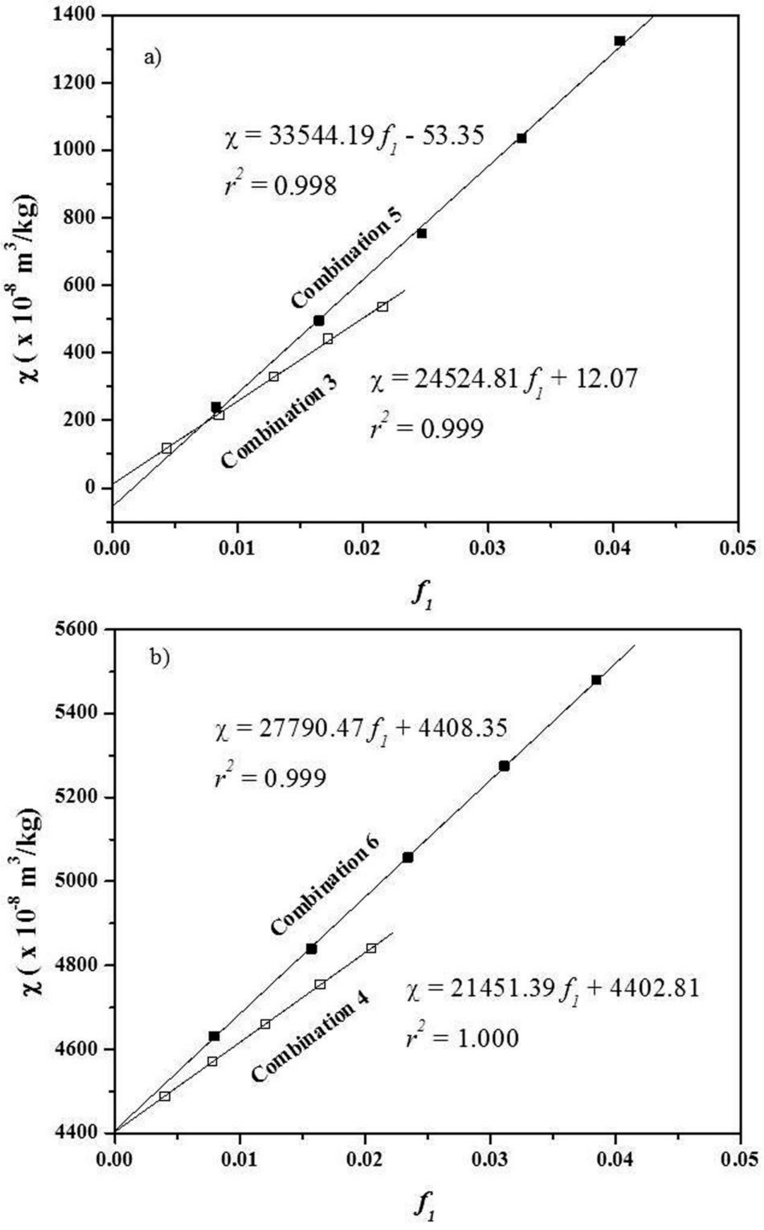

Figure 5. Plots of χ versus the fraction of tested substance f_1 in the experiments where MO-4232 and MO-7029 were combined with (a) plasticine (combination 3 and 5, respectively) and (b) R-9998 (combination 4 and 6, respectively).

Furthermore, the value of magnetic susceptibility to large extent depends on mineral purity as well as on granulometry (grain size and shape). Thus, despite of their similarity in mineralogy (both are magnetite as shown by XRD analyses) MO-4232 and MO-7029 have different values of mass-specific magnetic susceptibility. Their values, however, still fall within the range of that of magnetite (20 to 111 x 10^{-5} m^3/kg) described in Hunt *et al.* (1995).

The results of the third set of experiments were given in Figure 6a where good correlation between χ and f_1 was found for combination 7a consisting lateritic soil samples and YO-8087. The intercept of this combination is 119.49 x 10^{-8} m^3/kg which is very close to the expected 120.79 x 10^{-8} m^3/kg for that of YO-8087. The estimated mass-specific magnetic susceptibility of lateritic soil, using YO-8087 as reference substance, is found to be 2928.31 x 10^{-8} m^3/kg, which is about 2.8% lower than the standard value of

3011.24 x 10^{-8} m^3/kg listed in Table 2. Comparing this result with that of industrial substance, the less accurate estimation of mass-specific magnetic susceptibility for natural substances such as lateritic soil samples might arise from the fact that lateritic soils is not as homogeneous as industrial substances. Unlike the industrial substances, magnetic minerals in lateritic soils might vary both in composition as well as in grain sizes. Smaller amount of lateritic soils used in combinations 7a might have different composition of magnetic mineralogy compared to the fully-filled sample holder used in determining the standard mass-specific magnetic susceptibility. We measured other set of combination of lateritic soils with YO-8087 as combination 7b (Figure 6b) and found that there is slight difference in estimated magnetic susceptibility. The average estimated magnetic susceptibility of combination 7a and 7b is 2957.97 x 10^{-8} m^3/kg.

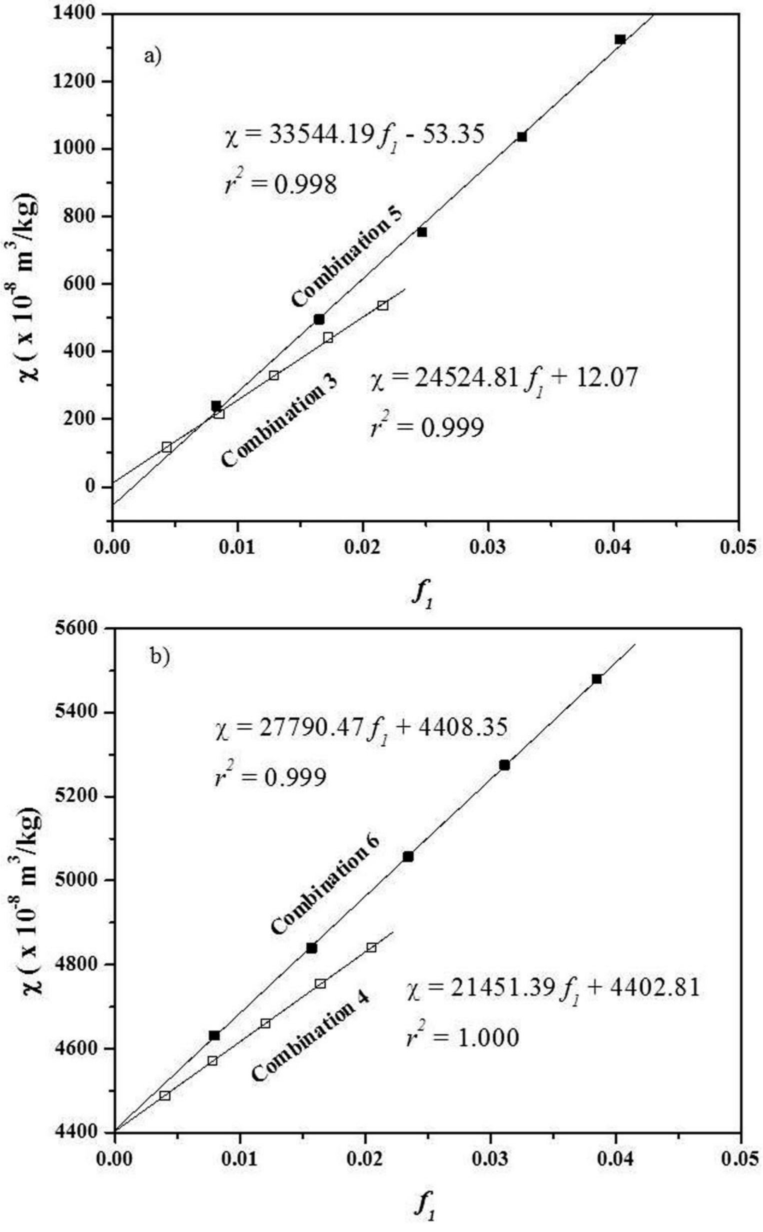

Figure 6. Plot of the ξ versus the fraction of tested substance f_1 in the experiments where lateritic soils, as tested substance, was combined with YO-8087 as reference substance in two combination (a) combination 7a and (b) combination 7b.

Figure 7 shows the results of the fourth set of experiments where low quantity samples represented by vehicle-derived particulates were combined with plasticine (combination 8) and common wheat flour (combination 9). As expected, correlations between χ versus f_1 in this set of experiments were not as good as that of industrial substances and lateritic soils. The value of r^2 is better for combination 8 (Figure 7a) compared to that of for combination 9 (Figure 7b) confirming the notion that the use of weaker reference substance might reduce the accuracy of estimation. However, the smaller values of r^2 in combinations 8 and 9 could also arise from the fact that vehicle-derived particulates are less homogeneous than industrial substances or lateritic soils.

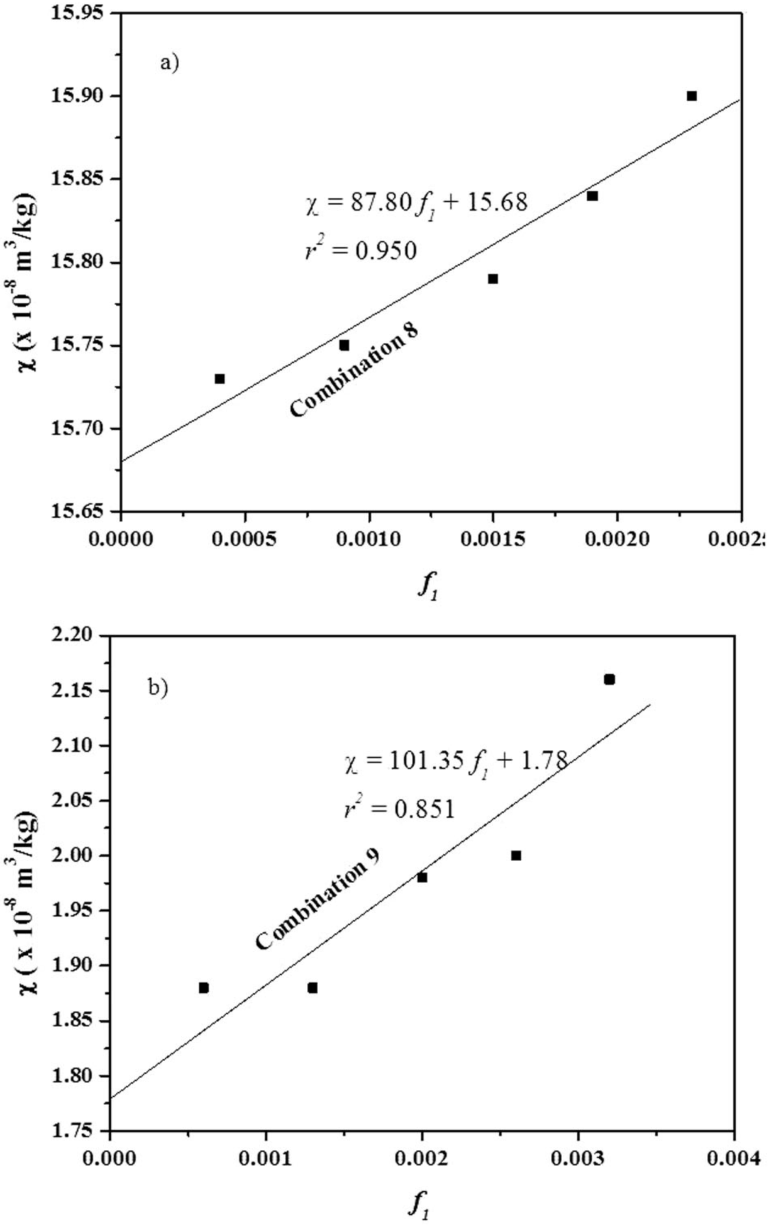

Figure 7. Plots χ versus the fraction of tested substance f_1 in the experiments where vehicle-derived particulates, as tested substance, were combined with (a) plasticine (combination 8) and (b) common wheat flour (combination 9).

In Figure 7a, the intercept is 15.68 x 10^{-8} m^3/kg which is very close to the expected 15.95 x 10^{-8} m^3/kg for plasticine. For combination 8, the estimated mass-specific magnetic susceptibility of vehicle-derived particulates is found to be 103.48 x 10^{-8} m^3/kg, which is about 2.9% smaller than the standard value of 106.61 × 10^{-8} m^3/kg listed in Table 2. In Figure 7b, the intercept is 1.78 x 10^{-8} m^3/kg which is similar to the expected value for that of common wheat flour (see Table 2). For combination 9, the estimated mass-specific magnetic susceptibility of vehicle-derived particulates is found to be 103.14 x 10^{-8} m^3/kg, which is about 3.3% smaller than the expected value of 106.61 x 10^{-8} m^3/kg. Although the results for combinations 8 and 9 are almost similar, the quality of estimation using magnetically stronger plasticine is better than that using the magnetically weaker common wheat flour. The measurement results of all combinations are summarized in Table 3.

	Statistically determined			Measured			
	Tested Substance (1)	Reference Substance (2)	χ^1-χ^2 (x 10^{-8} m^3/kg)	χ^2 (x 10^{-8} m^3/kg)	χ^1 (x 10^{-8} m^3/kg)	χ^1 (x 10^{-8} m^3/kg)	χ^2 (x 10^{-8} m^3/kg)
Combination 1	YO-8087	Plasticine	102.25±5.16	16.21±0.05	118.46±5.21	120.79±0.31	15.95±0.12
Combination 2	R-3098	Plasticine	64.87±2.89	16.39±0.03	81.26±2.93	82.06±0.17	15.95±0.12
Combination 3	MO-4232	Plasticine	24524.81±473.64	12.07±6.76	24536.88±480.41	25110±56.67*	15.95±0.12
Combination 4	MO-4232	R-9998	21451.39±72.09	4402.81±0.97	25854.20±73.06	25110±56.67*	4511.20±1.50
Combination 5	MO-7029	Plasticine	33544.19±760.34	-53.35±20.56	33490.84±780.91	30629±0.005*	15.95±0.12
Combination 6	MO-7029	R-9998	27790.47±179.94	4408.35±4.62	32198.82±184.56	30629±0.005*	4511.20±1.50
Combination 7a	Lateritic soils	YO-8087	2808.81±39.16	119.49±1.75	2928.30±40.91	3011.24±1.50	120.79±0.31
Combination 7b	Lateritic soils	YO-8087	2868.69±47.27	118.95±2.15	2987.64±49.43	3011.24±1.50	120.79±0.31
Combination 8	Vehicle-derived particulates	Plasticine	87.80±11.57	15.68±0.02	103.48±11.58	106.61±1.65	15.95±0.12
Combination 9	Vehicle-derived particulates	Flour	101.35±24.41	1.78±0.05	103.13±24.46	106.61±1.65	1.82±0.08

*Magnetic susceptibility was measured using a new instrument developed by Kodama (2010) at frequency of 500 Hz.

Table 3. Measurement results of the combining method for all combinations. Columns 4 to 6 represent statistically determined values of (χ_1–χ_2) as slopes of the straight lines, χ_2 as intercepts and χ_1 as slopes plus intercepts. These values were listed with their SE (standard error) values. Columns 7 and 8 represent values of χ_1 and χ_2 as they were measured in standard or full-size forms.

There are many cases in which accurate measurement of magnetic susceptibility is required. The accuracy is required, for example, in determining the threshold value between unpolluted and polluted soils. Hay *et al.* (1997) used a value of 38 x 10^{-8} m^3/kg to discriminate unpolluted and polluted soils containing significant anthropogenic particles from industrial processes in English top soils. Polluted soils have higher magnetic susceptibility (>38 x 10^{-8} m^3/kg). Meanwhile, comparing sanitary landfill leachate sludge for two different sites in Indonesia, Bijaksana and Huliselan (2010) found that correlation between magnetic parameters and heavy metal contents was found in only the site where the mass specific magnetic susceptibility is stronger (averaging 262.1 x 10^{-8} m^3/kg) but was absent in the other site where the mass specific magnetic susceptibility is weaker (averaging 155.3 x 10^{-8} m^3/kg).

This study has confirmed that measuring low quantity sample through placement in central zone of sensor still produces a significant error. The error is likely to be higher when the measured substance is relatively weak. For instance, measurement of moderately magnetic substance of YO-8087 produces greater error than measurement of strongly magnetic substance R-9998. Measuring low quantity sample in the central zone is analogue to the combining susceptibility method with air as the second or reference substance. The permeability, which is related to susceptibility, of air is much lower than permeability of sample, and then magnetic lines of flux in air are less dense than inside the sample (Collinson, 1983). Measuring low quantity sample placed in the central zone of sensor is expected to produce a significant error because there is a proportion of the magnetic flux which provides no contribution to induce magnetic field. Meanwhile, measurement of sample in larger quantity produces smaller error because the magnetic flux is greater as the magnetization of magnetic material produce magnetic field. Therefore, the error is minimized when air is replaced by any substances. Furthermore, the results of the experiments show that the quality of estimation to great extend depends on the choice of reference substances. In our experiments, the choice of reference substances whose mass-specific susceptibility is about 10-20% of that of tested substance provides a better estimation of the tested substances. As the method of magnetic susceptibility measurement improves, there are other new instruments in the market that might be able to measure the volume-specific magnetic susceptibility of strong magnetic samples properly. One of such instrument is the newly released MFKI multi-function Kappabridges (AGICO, Brno, Czech Republic) with measuring range of 0 to 0.9 SI (Advanced Geoscience Instruments Co., 2009).

Last, we propose the following procedure of combining susceptibility method for measuring substances that are either too low in quantity or magnetically too strong. Depending on how strong the sample magnetically, the procedure requires sample as little as 50 to 250 mg. First, after measuring the sample for its mass and its density, the sample is measured for its raw volume-specific magnetic susceptibility. Using the sample density, the quantity is then converted into raw mass-specific magnetic susceptibility. Appropriate reference substance can then be determined from substances whose mass-specific susceptibility is about 10-20% of raw mass-specific magnetic susceptibility of tested substances. Samples of five incremental quantities of tested substance placed inside small capsule and surrounded by matrices of reference substance are then measured for their volume-specific magnetic susceptibility. The measured quantities are then converted into raw mass-specific magnetic susceptibilities using their densities. The results are then plotted in a graph of raw mass-specific magnetic susceptibilities versus mass fractions of tested substance. The mass-specific magnetic susceptibility can then be determined form the slope of aforementioned graph.

5 Conclusions

We have shown that measuring low quantity sample for mass-specific magnetic susceptibility needs to be done cautiously as the common method of placing the sample in the central zone of the sensor is prone to significant error. To overcome this limitation, we proposed a combining susceptibility in which low quantity tested substance was combined with second or reference substance whose mass-specific magnetic susceptibility is known. Compared to the common method, the proposed method provides a better estimation of mass-specific magnetic susceptibility with a small amount of sample. The proposed method has been tested with variety of substances ranging from magnetically strong industrial substances to moderately weak particulates from vehicle exhaust. The use of common substances, such as plasticine with mass-specific magnetic susceptibility of 15.95 x 10^{-8} m^3/kg, is sufficiently accurate in estimating the mass-specific magnetic susceptibility of typical samples used in rock magnetism (≈ 100 to 200 x 10^{-8} m^3/kg). However, magnetically stronger tested substance (> 1000 x 10^{-8} m^3/kg) would require reference substances with mass-specific magnetic susceptibility of ≈ 100 x 10^{-8} m^3/kg or higher. In such cases, the use of industrial magnetic samples as reference substance is preferable.

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References

Advanced Geoscience Instruments Co., 2009. MFK1-FA/CS4/CSL User's Guide, Advanced Geoscience Instruments Co., Brno, Czech Republic, 62 pp.

Bartington Instruments Ltd., 2010. Operation Manual for MS2 Magnetic Susceptibility System (OM0408 Issue 48), Bartington Instruments Ltd., Oxford, U. K, 71 pp.

Bijaksana, S., Huliselan, E. K., 2010. Magnetic properties and heavy metal content of sanitary leachate sludge in two landfill sites near Bandung, Indonesia, *Environmental Earth Sciences, 60 (2),* 409-419.

Brachfeld, S., Banerjee, S. K., 2000. A new high-resolution geomagnetic paleointensity record for the North American Holocene: A comparison of sedimentary and absolute intensity data, *Journal of Geophysical Research, 105 (B1)*, 821-834.

Chaparro, M. A. E., Sinito, A. M., Ramasamy, V., Marinelli, C., Chaparro,M. A. E., Mullainathan, S., Murugesan, S., 2008. Magnetic measurements and pollutants of sediments from Cauvery and Palaru River, India, *Environmental Geology, 56 (2)*, 425-437.

Collinson, D. W., 1983. Methods in rock magnetism and paleomagnetism: Techniques and Instrumentation, Chapman and Hall, London, 503 pp.

Dearing, J. A., 1999. Environmental Magnetic Susceptibility: Using the Bartington MS2 System, Chi Publishing, Kenilworth, U. K, 104 pp.

Franco, D.R., Hinnov, L.A., Ernesto, M., 2012. Millennial-scale climate cycles in Permian–Carboniferous rhythmites: Permanent feature throughout geologic time?, *Geology*, *40 (1),* 19-22.

Geiss, C. E., Egli, R., Zanner, C. W., 2008. Direct estimates of pedogenic magnetite as a tool to reconstruct past climates from buried soils, *Journal of Geophysical Research, 113 (B11102),* 1-15.

Hay, K. L., Dearing, J. A., Baban, S. M. J., Loveland, P. J., 1997. A preliminary attempt to identify atmospherically-derived pollution particles in English topsoils from magnetic susceptibility measurement, *Physics and Chemistry of the Earth, 22 (1-2)*, 207-210.

Hunt, C. P., Moskowitz, B. M., Banerjee, S., 1995. Rock Physics and Phase Relations, A Handbook of Physical Constants ed. T Ahrens, American Geophysical Union, Washington, pp189-203.

Irurzun, M.A., Gogorza, C.S.G., Torcida, S., Lirio, J.M., Nunez, H., Bercoff, P.G., Chaparro, M.A.E., Sinito, A.M., 2009. Rock magnetic properties and relative paleointensity stack between 13 and 24 kyr BP calibrated ages from sediment cores, Lake Moreno (Patagonia, Argentina), *Physics of the Earth and Planetary Interiors*, *172 (3-4)*, 157-168.

Kodama, K., 2010. A new system for measuring alternating current magnetic susceptibility of natural materials over a wide range of frequencies, *Geochemistry, Geophysics, Geosystems, 11* (Q11002), 1-7.

Lecoanet, H., Lévêque, F., Segura, S., 1999. Magnetic susceptibility in environmental applications: comparison of field probes, *Physics of the Earth and Planetary Interiors, 115 (3-4)*, 191-204.

Li, J. H., Pan, Y. X., Liu, Q. S., Qin, H. F., Deng, C. L., Che, R. C., Yang, X. A., 2010. A comparative study of magnetic properties between whole cells and isolated magnetosomes of *Magnetospirillum magneticum* AMB-1, *Chinese Science Bulletin, 55 (1)*, 38−44.

Lu, S,, Bai, S., Cai, J., Xu, C., 2005. Magnetic properties and heavy metal contents of automobile emission particulates, *Journal Zhejiang University Science, 6B (8),* 731-735.

Maher, B. A., Moore, C., Matzka, J., 2008. Spatial variation in vehicle-derived metal pollution identified by magnetic and elemental analysis of roadside tree leaves, *Atmospheric Environment, 42 (2),* 364–373.

Marie, D. C., Chaparro, M. A. E., Gogorza, C. S. D., Navas, A., Sinito, A. M., 2010. Vehicle-derived emissions and pollution on the road Autovia 2 investigated by rock-magnetic parameters: A case study from Argentina, *Studia Geophysica et Geodaetica, 54 (1)*, 135-152.

Mooney, S. D,, Geiss, C., Smith, M. A., 2003. The use of mineral magnetic parameters to characterize archaeological ochres, *Journal of Archaeological Science, 30 (5),* 511-523.

Moskowitz, B. M., Bazylinski, D. A., Egli, R., Frankel, R. B., Edwards, K. J., 2008. Magnetic properties of marine magnetotactic bacteria in a seasonally stratified coastal pond (Salt Pond, MA, USA), *Geophysical Journal International, 174 (1)*, 75-92.

Muxworthy, A. R., Matzka, J., Davila, A. F., Petersen, N., 2003. Magnetic signature of daily sampled urban atmospheric particles, *Atmospheric Environment, 37 (29),* 4163–4169.

Petrovsky ,E., 2007. Susceptibility in Gubbins, D., Herrero-Bervera, E. (eds), *Encyclopedia of geomagnetism and paleomagnetism*, Springer, Dordrecht, 1054 pp.

Rada, M., Costanzo-Alvarez, V., Aldana, M., Campos,C., 2008. Rock magnetic and petrographic characterization of prehistoric Amerindian ceramics from the Dos Mosquises Island (Los Roques, Venezuela), *Interciencia*, *33 (2),* 129-134.

Safiuddin, L. O., Haris, V., Wirman, R. P., Bijaksana, S., 2011. A preliminary study of the magnetic properties on laterite soils as indicators of pedogenic processes, *Latinmag Letters, 1 (1),* 1-15.

Sanger, E. A., Glen, J. M. G., 2003. Density and Magnetic Susceptibility Values for Rocks in the Talkeetna Mountains and adjacent Region, South-Central Alaska*, Open-File Report 03-268* U S Geological Survey, Menlo Park, USA, 44 pp.

Spiteri, C., Kalinski, V., Rösler, W., Hoffmann, V., Appel, E., MAGPROX team., 2005. Magnetic screening of a pollution hotspot in the Lausitz area, Eastern Germany: correlation analysis between magnetic proxies and heavy metal contamination in soils, *Environmental Geology, 49 (1),* 1-9.

Torres de Araujo, F.F., Pires, M.A., Frankel, R.B. & Bicudo, C.E.M., 1986. Magnetite and magnetotaxis in algae, *Biophysical Journal, 50 (2)*, 375–378.

Xie, Q., Chen, T., Xu, H., Chen, J., Ji, J., Lu, H., Wang, X., 2009. Quantification of the contribution of pedogenic magnetic minerals to magnetic susceptibility of loess and paleosols on Chinese Loess Plateau: Paleoclimatic implications, *Journal of Geophysical Research, 114 (B09101)*, 1-10.

Yokoyama, Y., Yamazaki, T., Oda, H., 2007. Geomagnetic 100-ky variation extracted from paleointensity records of the equatorial and North Pacific sediments, *Earth, Planets and Space, 59 (7),* 795-805.