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# Hidden value in low-cost inorganic pigments as potentially valuable magnetic materials

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ABSTRACT

Inorganic pigments are substances that develop colour in organic solids such as ceramics and glazes, and are usually a complex mixture of oxides, and relatively low-cost. Their chromatic properties have been extensively studied, yet surprisingly the magnetic and electrical properties of these economic and common materials have been neglected, despite the fact many are based on ferrite spinels. Therefore, we investigated these properties in commercial black and brown pigments, to assess their potential as magnetic materials. The brown and black pigments were found to be spinel ferrites, with estimated formulas of $Fe_{1.34}Cr_{0.62}Mn_{0.66}Zn_{0.22}Ni_{0.10}Co_{0.06}O_4$ and $Fe_{1.02}Cr_{0.97}Co_{0.57}Mn_{0.23}Ni_{0.21}O_4$, respectively. The brown pigment also contained a higher amount of $SiO_2$ compared to the black pigment (~7 mol% vs. ~2 mol%), which appeared as a second phase of crystalline quartz, and adversely affected its porosity, magnetisation and electrical ac conductivity, compared to the black pigment. However, both were very magnetic and very soft ferrites. The brown pigment had $M_s$=11.7 A m$^2$ kg$^{-1}$ and $H_c$ of 1.5 kA m$^{-1}$, with a high electrical conductivity ($\sigma$) of $4\times10^{-4}-7\times10^{-3}$ $\Omega^{-1}$ m$^{-1}$ between 100 Hz and 1 MHz. The black pigment was equally magnetically soft, but had a much greater magnetisation and lower electrical conductivity, with $M_s$=18.7 A m$^2$ kg$^{-1}$, $H_c$=2.4 kA m$^{-1}$, and $\sigma=5\times10^{-6}-8\times10^{-5}$ $\Omega^{-1}$ m$^{-1}$ between 100 Hz and 1 MHz.

This work has revealed the potential hidden value of low-cost commercial inorganic pigments based on spinel ferrites as magnetic materials. This demonstrates their potential at low-cost alternative materials for applications such as in power supply transformers, switching materials and sensors, where soft magnetisation is especially important.



## 1. Introduction

Magnetic materials are hugely important to our industrialised and technological society (electric motors and generators, data storage, sensors and switches, etc.), and demand is still expected to sharply increase in future years [1]. Rare earth element alloys [2] and iron-oxide based ferrites [3] are by far the two most common types of magnetic material, used in a myriad of applications. However, prices have risen dramatically for rare earth elements due to Chinese export restrictions [4], which have stimulated investigations for alternative materials. Although they have inferior magnetisation, ferrites have lower production costs and higher availability, making them an interesting alternative for many devices and applications [3]. Therefore, new and low-cost magnetic materials for niche applications are eagerly pursued.

Inorganic pigments are substances that develop colour in organic solids, and are usually a complex mixture of oxides. They are produced from calcination at high temperatures of metal oxides, minerals or metal salts, with thermal stability being one of their most important properties [5]. Several metallic oxides are typically employed, including magnetic elements such as nickel, iron and cobalt [6,7]. Parameters such as pigment chemical composition, crystalline structure and resulting colour are used to classify the pigment class. Pigments of the spinel type are one of the most important groups [8,9]. The chromatic properties of these coloured materials have been extensively studied [10–12], yet surprisingly the magnetic and electrical properties of these relatively low-cost materials have been rather neglected. Nonetheless, the composition of inorganic pigments, often containing several magnetic elements, suggests the possibility of using them as magnetic materials.

In this work, two commercial inorganic pigments were characterised regarding their structural, morphological, electrical and magnetic properties, namely a black and a brown pigment. To the

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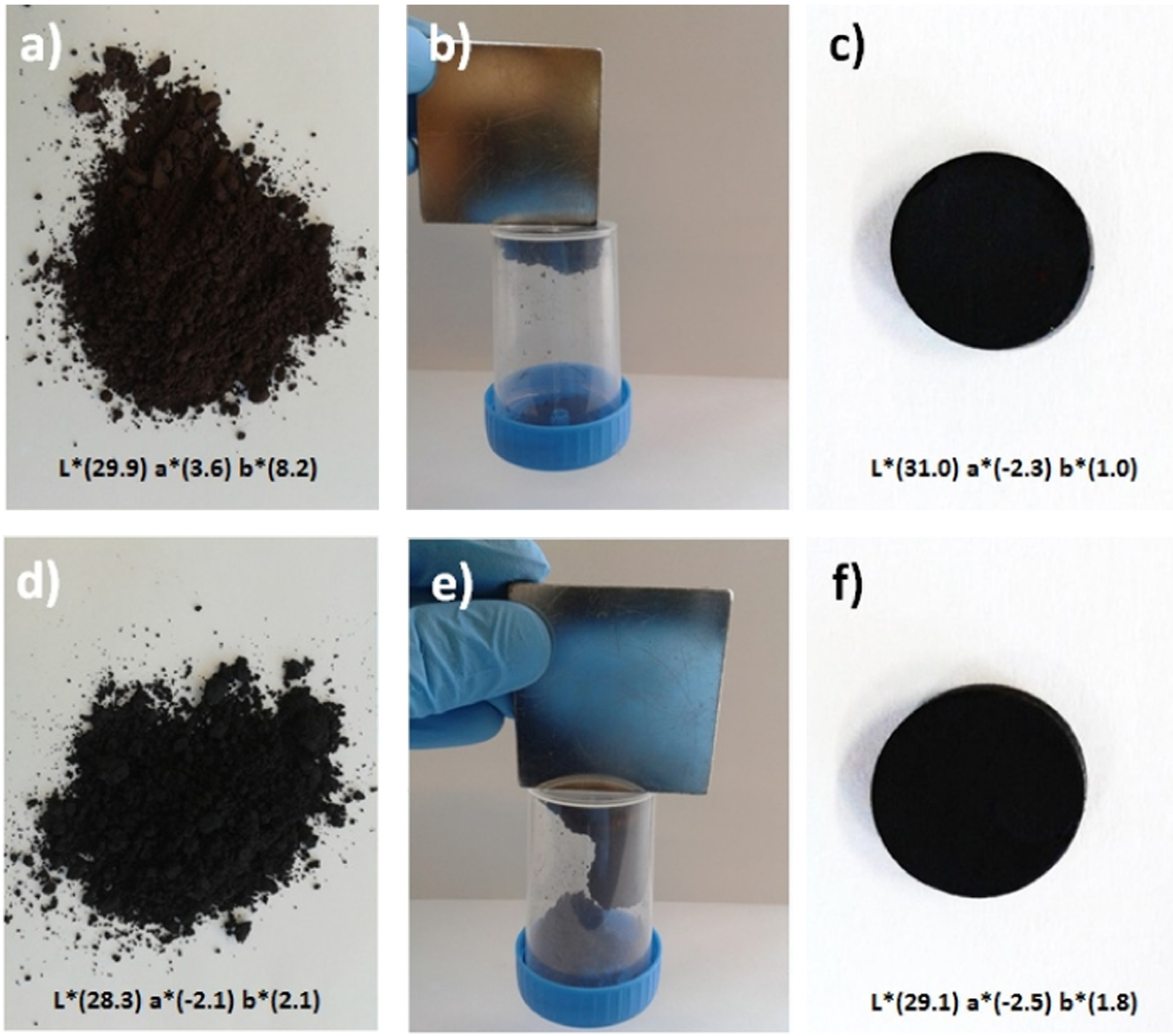


**Fig. 1.** L* a* b* colorimetric coordinates of the as-received commercial inorganic pigments (a and d), basic magnetic evaluation test (b and e) and corresponding sintered discs. Upper images correspond to the brown pigment while the lower ones to the black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

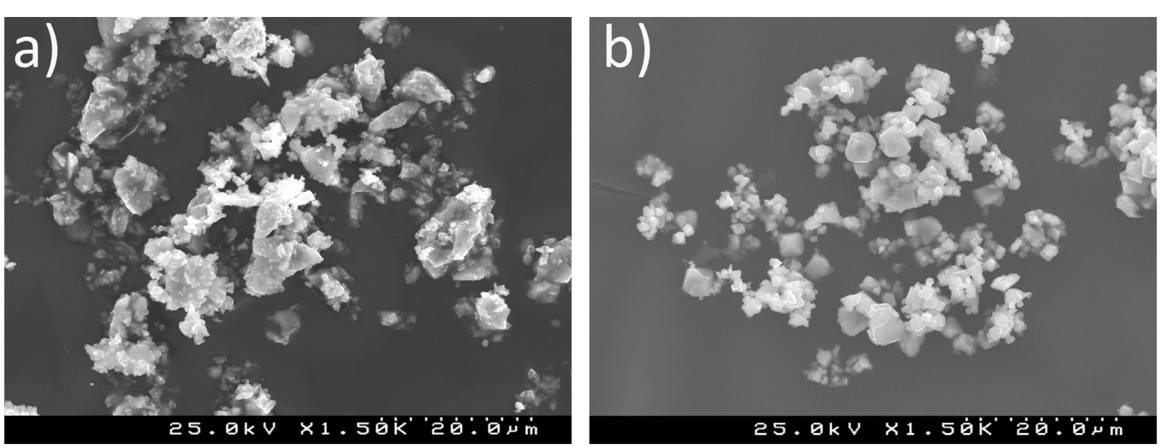


**Fig. 2.** SEM micrographs of commercial inorganic pigments: (a) brown and (b) black.

best of our knowledge, this is the first investigation concerning the magnetic and electrical characterisation of commercial inorganic pigments.

The brown pigment (5829-R) was selected due to its low price (~9 $/kg), which makes it economically attractive for industrial applications. Black pigments are probably the most widely used in