

Environmental blue CoAl_2O_4 pigment co-doped by Zn^{2+} and Mg^{2+} : synthesis, structure and optical properties

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Abstract: Nano-sized blue solid solutions $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x = 0 \sim 0.5$) have been synthesized by the Pechini method. Single-phase $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ with crystallite size of ~ 40 nm was identified by XRD measurement. The TG-DSC results indicated that the phase formation temperature of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ increased with the substitution of $\text{Zn}^{2+}/\text{Mg}^{2+} \rightarrow \text{Co}^{2+}$ proceeding. The UV-vis spectra illustrated that the $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment displayed the more intensive blue color with the strongest absorbance appearing within the visible region. The FT-IR spectra suggested that the inversion degree of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment reduces with the

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increase of Zn^{2+} rather than Mg^{2+} , enabling to control the pigment color by tuning the Zn^{2+} content. The FESEM images showed the irregular shaped morphology of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ crystal, different from cubic-like morphology of CoAl_2O_4 crystal. The XPS results illustrated that the inversion of pure CoAl_2O_4 pigment is larger than that of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$. Both $\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ were confirmed to enable the commercial potential in replacing the current CoAl_2O_4 pigments.

Keywords: Absorbance spectroscopy; Solid solutions; Citrate sol-gel method; Blue color; Inversion degree

1 Introduction

The natural and synthetic spinel-type (AB_2O_4) structure oxides, where divalent A and trivalent B cations occupy tetrahedral and octahedral crystallographic sites, respectively, have been widely used as ceramic pigments, magnetic materials and catalysts and so on. [1~4] Among them, Cobalt aluminate ($CoAl_2O_4$), known as Thenard's blue, is a typical blue inorganic pigment coupling with Co^{2+} ions in tetrahedral positions and Al^{3+} in octahedral positions. [5~8] This blue $CoAl_2O_4$ pigment has played a significant role in coloring our daily life, such as plastics coloring, paints, glasses, glazes and porcelain enamels. Except for its intensive blue color, the high resistance to acid and alkali and enhanced thermal stabilities are other prominent features of this inorganic blue pigment which should be highlighted. [9]

Recently, much researching enthusiasm has focused on how to obtain commercial $CoAl_2O_4$ pigment by optimizing the preparing process. The $CoAl_2O_4$ pigment is traditionally synthesized by solid-state reactions which involve the mechanical mixing of cobalt and aluminum oxides followed by calcinations at ~ 1300 °C for over 2h as well as an extended grinding process. [3,10~12] However, this process requires a long-range diffusion of metal ions, which may result in a poor control of stoichiometry and inhomogeneous grains. [13] It is well known that

various wet-chemical methods have already shown advantages over solid-state reactions in the synthesis of nano-sized CoAl_2O_4 particles, including sol-gel method [14], hydrothermal treatment [15~16], Pechini method [17~18], reverse micro-emulsion method [19] and combustion method [20], and so on. These methods can effectively solve the above problems in solid-state process, so the Pechini method will be adopted in this paper.

Moreover, as the main contributor for generating blue color of CoAl_2O_4 pigment, the cobalt element has already aroused great issues of both toxicity and scarcity. The hazardous cobalt element is widely considered to have an environmental impact on the industrial manufacturing process. Also, being a rare natural resource, the use of cobalt element assuredly aggrandizes the production costs. In these respects, the most direct practice is to reduce the amount of Co^{2+} in CoAl_2O_4 spinel by adding some alternative elements, such as Zn^{2+} and/or Mg^{2+} . This procedure can not only reduce the utilization of expensive and toxic cobalt element but also produce commercial pigment with promoted performance. The improvement of structure and optical properties of CoAl_2O_4 pigments by Zn^{2+} and Mg^{2+} ions doping can be confirmed by the following efforts: $\text{Zn}_{1-x}\text{Co}_x\text{Al}_2\text{O}_4$ [8,17], $\text{Co}_x\text{Mg}_{1-x}\text{Al}_2\text{O}_4$ [21], as well as $\text{Zn}_{2-x}\text{Co}_x\text{SiO}_4$ [22], $\text{Co}_{1-x}\text{Zn}_x\text{Cr}_{2-y}\text{Al}_y\text{O}_4$ [7], $\text{Mg}_{2-x}\text{Co}_x\text{Al}_4\text{Si}_5\text{O}_{18}$ [23], and so on. The pigments of $\text{Mg}_x\text{Co}_y\text{Al}_2\text{O}_4$ type were

also proved to enable to present different colors, depending on particle shape and size, bulk density, and doping concentrations. Meanwhile, the pigments of $\text{Zn}_x\text{Co}_y\text{Al}_2\text{O}_4$ type exhibited the blue color ranging, markedly NIR solar reflectance and NIR reflective performance with Zn^{2+} ions replacing Co^{2+} ions in part. [7~8, 31] Nonetheless, there exists scarcely related literatures about the influence of co-doping Zn^{2+} and Mg^{2+} ions in structure and optical properties of CoAl_2O_4 blue pigments. To make aforesaid issue clearly, we performed the investigations on spinel-type nano-sized crystalline $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment.

In this study, the precursor powders of crystalline $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x=0, 0.1, 0.2, 0.3, 0.4, 0.5$) were synthesized by the Pechini method and then calcined at 250 °C for 2h to form the final nano-sized pigments. The influences of relative content of Zn^{2+} and Mg^{2+} on morphological feature and crystal structure of particles as well as structural and optical properties of the pigments were investigated in detail. The optimal samples were selected for potential commercial applications.

2 Experimental

2.1 Materials and synthesis

All the raw chemical reagents are analytical pure grade: zinc acetate dehydrate ($\text{C}_4\text{H}_6\text{ZnO}_4 \cdot 2\text{H}_2\text{O}$), magnesium acetate tetrahydrate ($\text{C}_4\text{H}_6\text{MgO}_4 \cdot 4\text{H}_2\text{O}$), cobalt nitrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), aluminum nitrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$), citric acid (CA) and ethyl alcohol (EA), which were all provided by Sinopharm Chemical Reagent Co., Ltd, Shanghai, China. The Standard commercial CoAl_2O_4 blue pigment (BU612) was used as a reference pigment, which was purchased from Nanjing Pigments Tech. Co., Ltd.

The polymeric precursor method was selected to synthesize polycationic powders. This method is based on three parts: the cations chelation by citric acid (CA) in an aqueous solution, the polyesterification between carboxylic groups of CA and hydroxyl groups of EA forming polycationic resin when heating and stirring.[4, 24~25] In our experiment, 0.015 mol $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 0.06 mol $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were firstly dissolved in 100 ml distilled water under constant magnetic stirring at 60 °C for 30 min., following by the addition of 0.27 mol CA and the solution was stirred for another 30 min. at 60 °C. Meanwhile, 0.03x (x=0, 0.1, 0.2, 0.3, 0.4 and 0.5) mol $\text{C}_4\text{H}_6\text{ZnO}_4 \cdot 2\text{H}_2\text{O}$ and 0.03(0.5-x) mol $\text{C}_4\text{H}_6\text{MgO}_4 \cdot 4\text{H}_2\text{O}$ were also dissolved in EA completely at 60 °C for 1h. These samples are named as ZM2~7, while ZM1 is the pure CoAl_2O_4 crystal without any Zn^{2+} and Mg^{2+} doping. The molar ratios of metal/(CA) and (EA/CA) were set as 1:3 and 2:3, separately. Subsequently, the

aforesaid EA was added into CA solutions and kept further stirring for 2 h at 80 °C. During the process of removing excess water through continuous heating, the purple solution became more and more viscous until a xerogel formed. [4] Ultimately, the xerogel was underwent a preliminary heat treatment at 250 °C for 2 h in air, to remove most of organic solvents and water. [8] After that, the dry xerogel was milled into a fine powder followed by a calcination at 1000 °C for 2h in air. The flow chart of the whole preparing process is exhibited in Fig. 1.

2.2 Measurements and characterization

The thermal behavior of pigment precursors was examined by a thermogravimetry and differential scanning calorimetry analyzer (TG-DSC, Netzsch STA 449 F3 instrument). Alumina was used as a reference material. The TG-DSC curves were recorded at a heating rate of 10 °C·min⁻¹ over the temperature range of 25 ~ 1000 °C, inflowing air rate of 20 mL·min⁻¹. The crystal structures and phase composition of sintered pigments were characterized by X-ray diffraction (XRD, D/MAX-UltimaIV, Rigaku). The Cu $K\alpha$ radiation ($\lambda = 0.15405 \mu\text{m}$) was used at 40 KV and 40 mA. The diffraction patterns were recorded with $2\theta = 10^\circ \sim 70^\circ$. UV-vis diffuse reflectance spectra (UV-vis DRS) were signed in the absorbance mode at room temperature in the range of 300 ~ 800 nm on Lambda 750 S apparatus, using BaSO₄ as a reference material. Fourier transform infrared (FT-IR) spectra were recorded on Thermo

Nicolet NEXUS equipment with a Nicolet 750 spectrometer. The commission internationale de L'eclairage (CIE- $L^*a^*b^*$) values were measured by a spectrophotometer (CM-2600d), in which L^* is the lightness axis [black (0), white (100)], a^* is the green (–) to red (+) axis, and b^* is the blue (–) to yellow (+) axis. The particle size and morphology of calcined pigment were observed by a field emission scanning electron microscope (FE-SEM, Zeiss Ultra Plus) instrument. The X-ray photoelectron spectra (XPS) were measured by ESCALAB 250Xi spectrometer with mono-chromatized Al $K\alpha$ X-ray radiation in ultrahigh vacuum ($<10^{-7}$ Pa). The binding energies were calibrated by taking C1s peak (284.6 eV) of adventitious carbon as a reference. The peaks were deconvoluted after background subtraction, using a mixed Gaussian-Lorentzian function. Fractional atomic concentrations of the elements were calculated using empirically derived atomic sensitivity factors. [26]

3 Results and discussion

3.1 Thermal analysis

The TG-DSC curves of two typical precursors (CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$) are shown in Fig. 2, which indicates that the whole phase formation process can be divided into three steps. The first

endothermic peak at ~ 80 °C and the adjacent weak endothermic peak at ~ 130 °C are observed due to the elimination of the co-ordination water and the decomposition of remaining nitrates and acetates in samples, respectively, coupling with a mass loss of $\sim 10\%$ in the first range of $0 \sim 200$ °C [14, 21]. The DSC curves from 200 °C to 700 °C exhibit two obvious exothermic peaks, where the exothermic peak at ~ 400 °C is attributed to the burning of organics [21] while the exothermic peak at ~ 500 °C corresponds to the formation of CoAl_2O_4 crystal. [2] There is also a more distinct mass loss of about 60% at temperature higher than 200 °C. The last step is the formation of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ compound with a feeble exothermic peak at ~ 700 °C and no evident mass loss was detected on TG curve (see Fig. 2a), which is in accordance with the findings by Zayat et al and Kurajica et al [6, 14].

Although the main exothermic and endothermic peaks of both CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ exhibited in Fig. 2 are very alike at the temperature below 450 °C, there still exist some minor differences between two samples at higher temperature. Obviously, after adding Zn^{2+} and Mg^{2+} into CoAl_2O_4 , the strongest crystalline peak position was shifted from ~ 446 °C of CoAl_2O_4 in Fig. 2 (a) to ~ 478 °C of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ in Fig. 2 (b) and the intensity of the exothermic peak was enhanced as well. Zn^{2+} and Mg^{2+} have approximate ionic radius to Co^{2+} (0.074 nm for Zn^{2+} , 0.072 nm for Mg^{2+} and 0.0745 nm for Co^{2+} ,

respectively), which facilitates the substitution of the Co^{2+} by Zn^{2+} and Mg^{2+} during the formation process of CoAl_2O_4 spinel crystallite. The small difference in ionic radii could still lead to the deformation of the unit cell and the ions transferred strenuously, which exhibits a higher crystallizing temperature and a stronger exothermic intensity in DSC curves as shown in Fig. 2 (b). Moreover, the DSC and TG curves in Fig. 2 illustrate that no further chemical or physical reactions occurred at 700 °C above, implying the end of the redox processes at 700 °C.

3.2 Crystal formation and structure analysis

The XRD patterns of pigments, CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x=0.1, 0.2, 0.3$ and 0.4) synthesized at 1000 °C for 2h, are illustrated in Fig. 3. The observed diffraction peaks in the pattern (a) are in good agreement with those of standard CoAl_2O_4 spinel (JCPDS card NO.: 44-0160). No traces of other impurity phases can be observed. The typical diffraction peaks in XRD patterns of (b) ~ (e) for $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x=0.1\sim 0.4$) can be identified as the standard spinel crystals, CoAl_2O_4 spinel (JCPDS card NO.: 44-0160), ZnAl_2O_4 spinel (JCPDS card NO.: 05-0669) and MgAl_2O_4 spinel (JCPDS card NO.: 21-1152). The phase analysis manifests that the main phases of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ powders, cubic spinel structure and space group $\text{Fd}\bar{3}\text{m}$, exist in a form of solid-solution.

Based on XRD patterns (b) ~ (e) of the $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ samples, the effect of varying x values on the crystallization behavior of CoAl_2O_4 spinel crystal was studied. With the increase of x value, both [3 1 1] and [3 3 1] peak intensities increase initially but decrease afterwards, though both peak intensities were still stronger than those of pure CoAl_2O_4 crystal phase. Furthermore, the relative intensities of the [2 2 0] and [3 1 1] peaks enhance and reach maxima when x reaches 0.4 ($\text{Zn}_{0.4}\text{Mg}_{0.1}\text{Co}_{0.5}\text{Al}_2\text{O}_4$), which is also coupled with a small shift of [3 1 1] from 36.78° to 36.84° . These peak intensity and position changes were associated with the small change of lattice deformation which was caused by the co-substitution of Zn^{2+} and Mg^{2+} . [7]

The average crystallite size (D_{hkl}) of the samples was calculated by Debye-Scherrer formula, [7, 27]

$$D_{\text{hkl}} = \frac{K \cdot \lambda}{\beta \cdot \cos \theta}$$

where β is the breadth of the observed diffraction line at its half-intensity maximum; K the shape constant and usually a value of about 0.9; λ the wavelength of the $\text{Cu}=\text{K}_\alpha$ radiation (1.5406 Å); θ the diffraction angle. The average D_{hkl} of the samples were listed in Table 1, which were found to be in the nano-sized range of 39-43 nm. Because citric acid was introduced into this mixture, the organic ligand capped the nanocrystals surface, thus inhibiting the growth of the particles. [4] However,

$\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ sample possesses the minimum crystallite size 39 nm among all samples with various molar ratios of Zn^{2+} and Mg^{2+} , as seen in Table 1.

3.3 XPS spectra analyses

In our experiment, the chemical states of the elements on the surface region of as-synthesized pigments CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ are characterized by X-ray photoelectron spectroscopy (XPS) and the results are shown in Fig. 4. The spectra indicate that no other elements were detected except for the original components and contaminated carbon. The C 1s peak at about 284.6 eV was used as a reference, while O 1s peak shows asymmetric and fixed on 531.5 ± 0.2 eV which is in accordance with that of O 1s in bulk CoAl_2O_4 reported by Patterson et al.. [41]

The coordination change of Co^{2+} and Al^{3+} in the surface region of pigments doped by Zn^{2+} and Mg^{3+} can be observed by the Co 2p and Al 2p peaks in Fig. 7b and d. The Co 2p_{3/2} core level peak is fixed at 781.9 eV with the broad satellite around 786.6 eV after deconvolution and that of Co 2p_{1/2} is 797.2 eV with the broad satellite about 803.7 eV, respectively, which are similar to the results reported by Zsoldos et al. [42] and Chung et al.. [43] All the Co 2p spectra are relatively broad and asymmetric, indicating that the Co^{2+} occupies both octahedral and tetrahedral coordination positions in as-synthesized samples. In addition,

the main peaks at lower binding energy (781.9 eV and 797.2 eV) can be ascribed to Co^{2+} ions placed at the octahedral sites, while the broad peak at higher binding energy (786.6 eV and 803.7 eV) are attributed to Co^{2+} fixed on tetrahedral positions. Similarly, the Al 2p peaks are focused on around 74.5 eV and 74.0 eV after deconvolution, which are due to octahedral Al^{3+} ions and tetrahedral Al^{3+} ions, separately.

Furthermore, the tetrahedral Co^{2+} ions and tetrahedral Al^{3+} ions are dominant in all the studied samples. On the basis of above discussion, the as-synthesized CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments can be treated as a partially inversed spinel-structure. The inversion parameter k can be estimated according to the area ratio of the two peaks, which correspond to the Co^{2+} and Al^{3+} on octahedral and tetrahedral sites, respectively. In our experiment, the k value for CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments are 0.20 and 0.01, respectively. The result indicates that the inversion degree of pure CoAl_2O_4 pigment is larger than that of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment. Also, the inverse degree are related to the particle size, and the increasing k will decrease the small particle size, fitting with the reports by Duan et al.. [2]

3.4 Surface morphology analyses

The surface morphology of the synthesized CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments was investigated by FE-SEM and the results were illustrated in Fig. 5. From the above images (a) ~ (d), it is

clearly shown that the particles of two samples have diverse surface morphologies with the particle size ranging from 30 nm to 100 nm. The cubic-like morphology was obviously observed in the case of CoAl_2O_4 powders, which is different from the irregular shaped morphology of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ powders. Besides, the addition of Zn^{2+} and Mg^{2+} would reduce the uniformity of particles of CoAl_2O_4 pigment. Additionally, the particles of CoAl_2O_4 sample tend to be more agglomerate than that of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ powders.

3.5 UV-vis spectra analyses

Fig. 6 illustrates the UV-vis absorbance spectra of (a) CoAl_2O_4 ; $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ system: (b) $x=0$; (c) $x=0.2$; (d) $x=0.3$; (e) $x=0.5$ calcined at 1000°C for 2h and (f) BU612 commercial blue CoAl_2O_4 pigment. All the spectra manifest a common feature: a strong and triple absorption band can be observed from 540 nm to 650 nm, which is within the visible region (400 nm ~ 780 nm). According to Tanabe Sugano energy level diagrams, the Co^{2+} in $[\text{CoO}_4]$ with d^7 configuration, ^4F ground state term splits into three terms $^4\text{A}_2$, $^4\text{T}_2$ and $^4\text{T}_1(\text{F})$ as well as ^4P excited state term changes to $^4\text{T}_1(\text{P})$. Thereby, the three spin allowed transitions are as follows: $\nu_1: ^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_2(\text{F})$; $\nu_2: ^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_1(\text{F})$ and $\nu_3: ^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_1(\text{P})$, with the first two bands in the IR region while the third band in the visible region.[28~29] The third spin allowed $^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_1(\text{P})$ transition of Co^{2+} ions in tetrahedral sites divides into three secondary

bands (see in Fig. 4) ~550 nm (peak I), ~580 nm (peak II) and ~620 nm (peak III), respectively.

As for many inorganic Co-based blue pigments with a spinel structure, the Co^{2+} ions located on tetrahedral sites play a crucial role in the pigments expressing blue color [8, 30]. To be more specific, spin-allowed $^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_1(\text{P})$ transition of the Co^{2+} ions in tetrahedral sites is corresponding to the absorption of the colors, such as, yellow, orange and red, thus the reflectance occurs in the complementary colors, such as, violet, blue and cyan, but centered in the blue color.[31] Furthermore, the absorption peak at ~481nm (peak IV) is influenced by the spin forbidden $^4\text{A}_2(\text{F}) \rightarrow ^2\text{T}(\text{G})$ transition of Co^{2+} ions in octahedral positions of spinel structure, while this new band results in green color.[2, 14, 32] The same band generated by octahedrally coordinated Co^{2+} has also been reported by other authors.[33~34] Other weak bands marked at ~400 nm (peak V) are also associated with the spin forbidden transition presented by Zayat et al. [14]

In our present work, the different substituting effect of Zn^{2+} and Mg^{2+} on exhibiting the blue color of CoAl_2O_4 pigment can be obtained according to the degree of the third spin allowed $^4\text{A}_2(\text{F}) \rightarrow ^2\text{T}(\text{G})$ transition as well as absorbance intensity of three peaks (I, II and III) in UV-vis absorbance curves as shown in Fig. 6. With the x value increasing, the absorbance intensity of three peaks (I, II and III) of $\text{Zn}_x\text{Mg}_{0.5-}$

$x\text{Co}_{0.5}\text{Al}_2\text{O}_4$ system pigments climbed up primarily, reached the maximum at $x = 0.3$ and then declined gradually. Namely, the Zn^{2+} plays a more important role in promoting the blue color of CoAl_2O_4 pigment than Mg^{2+} when x value is less than 0.3 but that would be completely opposite when x value is larger than 0.3. According to the decisive effect of the triplet band absorption pattern (peaks I, II and III) on the blue color generation, the $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment shows the most intensive blue color which is also stronger than that of commercial CoAl_2O_4 blue pigment (BU612). These findings can also be confirmed by the related UV-vis results in Fig. 6 and the pictures of pigments in Fig. 8. In other words, from the view of developing environmental pigment, the $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments with enhanced blue color can be selected as an alternative for current commercial CoAl_2O_4 pigment due to lowering the usage of Co element.

3.6 FT-IR spectra analyses

FT-IR analysis was conducted to characterize the resulting pigments subjected to the heat treatment at 1000°C for 2h and the results are presented in Fig. 7. The spectra shows two obvious absorption bands at around $662\text{-}681\text{ cm}^{-1}$ and $555\text{-}560\text{ cm}^{-1}$ and a weak absorption band at about $507\text{-}509\text{ cm}^{-1}$, associated with the vibrations of metal-oxygen, aluminum-oxygen and metal-oxygen-aluminum, respectively. [4] The

changes of absorption intensity with x ranging from 0 to 0.5 are the most apparent for the bands at the highest wave numbers. The band centered at $\sim 681\text{ cm}^{-1}$ dominates for $\text{Mg}_{0.5}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments, which is different from other four samples. Dominance shifts to the two bands centered at $\sim 673\text{ cm}^{-1}$ and $\sim 560\text{ cm}^{-1}$ with the increase of Zn^{2+} ions in the spinel structure. All the three bands at $\sim 673\text{ cm}^{-1}$, $\sim 560\text{ cm}^{-1}$ and $\sim 507\text{ cm}^{-1}$ of $\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments show the strongest absorption intensity among all the samples. What's more, the absorption intensity of these three bands of $\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ is much higher than that of ether synthetic CoAl_2O_4 or commercial CoAl_2O_4 pigment.

In literatures, the spinel crystals should exhibit three normal vibrational modes in the middle IR region, whereas various factors can lead to an increase in the number of IR modes. [35~36] Wang et al. [37] and Chapskaya et al. [38] have found that for normal CoAl_2O_4 spinel the vibrations occur at $\sim 666\text{ cm}^{-1}$, $\sim 554\text{ cm}^{-1}$ and $\sim 504\text{ cm}^{-1}$, comparing to these characteristic bands of inverse spinel occurred at $\sim 626\text{ cm}^{-1}$, $\sim 559\text{ cm}^{-1}$ and $\sim 480\text{ cm}^{-1}$. The absorption band at $\sim 666\text{ cm}^{-1}$ is generally assigned to the Al-O stretching vibration of the $[\text{AlO}_6]$ octahedral in normal spinel, while the absorption band at $\sim 626\text{ cm}^{-1}$ points out the tetrahedrally coordinated aluminum, which exists in inverse spinel. The bands at $555\text{--}560\text{ cm}^{-1}$ are identified as (CoO_4) , (ZnO_4) and (MgO_4) vibrations which are in agreement with the findings by Chen et al [39]

and Ahmed et al. [21] What's more, Meyers et al [40] ascribed 470-900 cm^{-1} and 340-550 cm^{-1} to the Al-O and Co-O stretching frequencies, respectively, whereas the Al-O-Co frequencies were noted in the 450-800 cm^{-1} region.

The band at the highest wave number intensively concentrates at $\sim 673 \text{ cm}^{-1}$, which could be related to the $[\text{AlO}_4]$ as well as inverse spinel. The different relative intensities of absorption bands at $\sim 673 \text{ cm}^{-1}$ decrease with the increase of Zn^{2+} ions content, indicating that Zn^{2+} shows a more obvious inhibiting effect in CoAl_2O_4 spinel being inversed than Mg^{2+} . However, more work needs to be done to reveal the inner relation between Zn^{2+} & Mg^{2+} and the inverse degree of CoAl_2O_4 spinel.

3.7 CIE- $L^*a^*b^*$ color measurement

The color changes of Co-based pigments were investigated and the results are shown in Fig. 8. It's obvious that the blue color of the CoAl_2O_4 pigment is darker than that of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments, in accordance with the decreasing L^* values in Table 1. Besides, with the increase of x value from 0 to 0.5, the colors of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments are hardly distinguished by human eye, whereas the weakened difference can be confirmed by changes of L^* and b^* . When the ratio of $\text{Zn}^{2+}/\text{Mg}^{2+}$ was 3:2 or 4:1, the more negative b^* values of pigments were measured, -28.27 and -27.98, respectively, which are more negative than the rest of samples. Moreover, for the extreme composition, the changes

of b^* of $\text{Zn}_{0.5}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x = 0.5$) is negligible comparing with $\text{Mg}_{0.5}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x = 0$), whereas the L^* values increase largely from 33.26 to 44.88, indicating that the substituting Zn^{2+} ions are more likely to the lighter pigments. Hence, taking the application of pigment into consideration, the $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ and $\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments can be used as an environmental blue coating pigment for replacing the current CoAl_2O_4 pigment.

4 Conclusions

In conclusion, blue pigments CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x=0, 0.1, 0.2, 0.3, 0.4, 0.5$) solid-solution nanocrystals have been successfully synthesized by Pechini method. The effects of Zn^{2+} and Mg^{2+} enrichment on the crystal formation, morphological and optical properties were investigated. TG-DSC and XRD results show that the substitution of $\text{Zn}^{2+}/\text{Mg}^{2+}$ to Co^{2+} can increase the phase formation temperature of $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ solid-solution typed crystals with a particle size of 39-43 nm. According to the UV-vis results, the triple absorption bands from 540 nm to 650 nm are related to the spin-allowed $[^4\text{A}_2(\text{F}) \rightarrow ^4\text{T}_1(\text{P})]$ transition of tetrahedral Co^{2+} in spinel structure. Besides, the $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment has stronger absorbance than other $\text{Zn}^{2+}/\text{Mg}^{2+}$ doping pigments within the visible region, which shows the more intensive blue color. FT-IR spectra revealed that the increase of

substituting Zn^{2+} ions content can reduce the inversion degree of CoAl_2O_4 spinel structure, which is more obvious than that of Mg^{2+} . Moreover, the difference of blue color of as-synthesized pigments can hardly be distinguished by human eye, but both $\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ show the potential commercial application. FESEM images indicate the different surface morphology of CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments, cubic-like and irregular shape, respectively. XPS results show that the Co^{2+} and Al^{3+} ions occupy both the tetrahedral and octahedral sites in cubic spinel structure. The inversion degree of pure CoAl_2O_4 pigment is larger than that of $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigment.

5 Acknowledgements

Authors are grateful to the Chinese Government's Fundamental Research Funds for the Central Universities (2016-JL-002) and Glass and Technology Research Institute of Shahe, China.

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Figure captions

Fig. 1 The flow chart of preparing process for $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ powders

Fig. 2 TG-DSC curves of pigment precursors: (a) CoAl_2O_4 and (b) $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ (ZM5) preliminarily heated at 250°C for 2 h

Fig. 3 XRD patterns of pigments: (a) CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ system: (b) $x=0.1$; (c) $x=0.2$; (d) $x=0.3$; (e) $x=0.4$

Fig. 4 XPS spectra of the as-synthesized CoAl_2O_4 and $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ nano-sized crystal calcined at 1000°C for 2h

Fig. 5 FESEM images of the (a) undispersed and (b) dispersed CoAl_2O_4 pigments; (c) undispersed and (d) dispersed $\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ pigments

Fig. 6 UV-vis absorbance spectra of pigments: (a) CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ system: (b) $x=0$; (c) $x=0.2$; (d) $x=0.3$; (e) $x=0.5$; (f) commercial CoAl_2O_4 pigment (BU612).

Fig. 7 FT-IR spectra of (a) CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$: (b) $x = 0$; (c) $x = 0.2$; (d) $x = 0.3$; (e) $x = 0.5$ calcined at 1000°C for 2h; (f) commercial CoAl_2O_4 pigment (BU612).

Fig. 8 Photographs of the (a) CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{1-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$: (b) $x=0$; (c) $x=0.3$; (d) $x=0.4$; (e) $x=0.5$ pigments; (f) commercial CoAl_2O_4 pigment (BU612).

Figures:

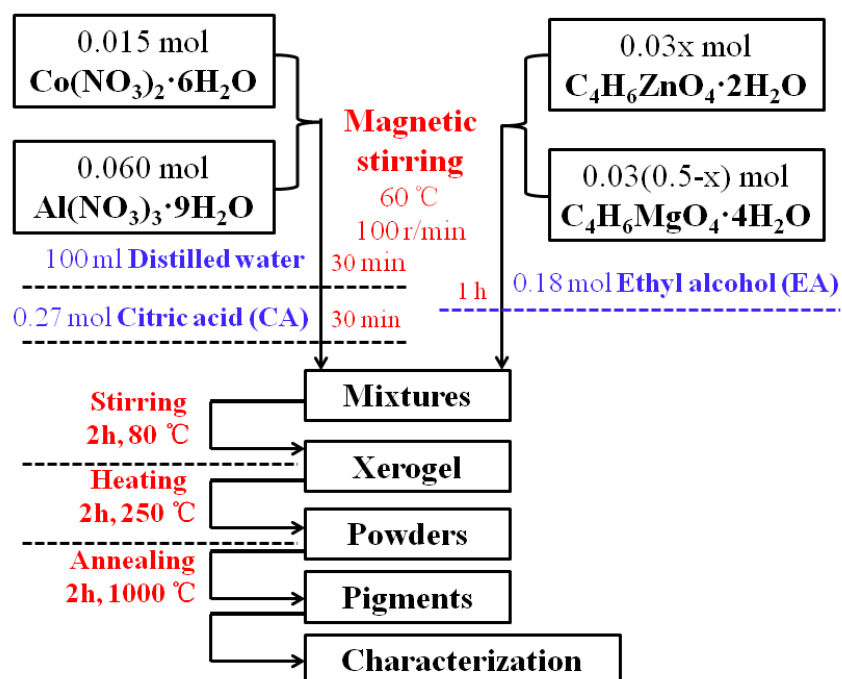


Fig. 1

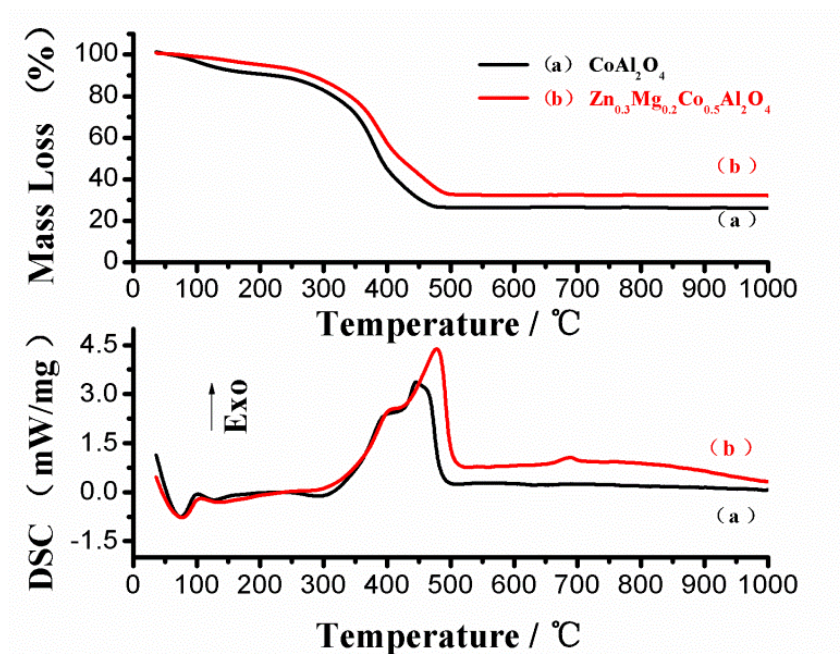


Fig. 2

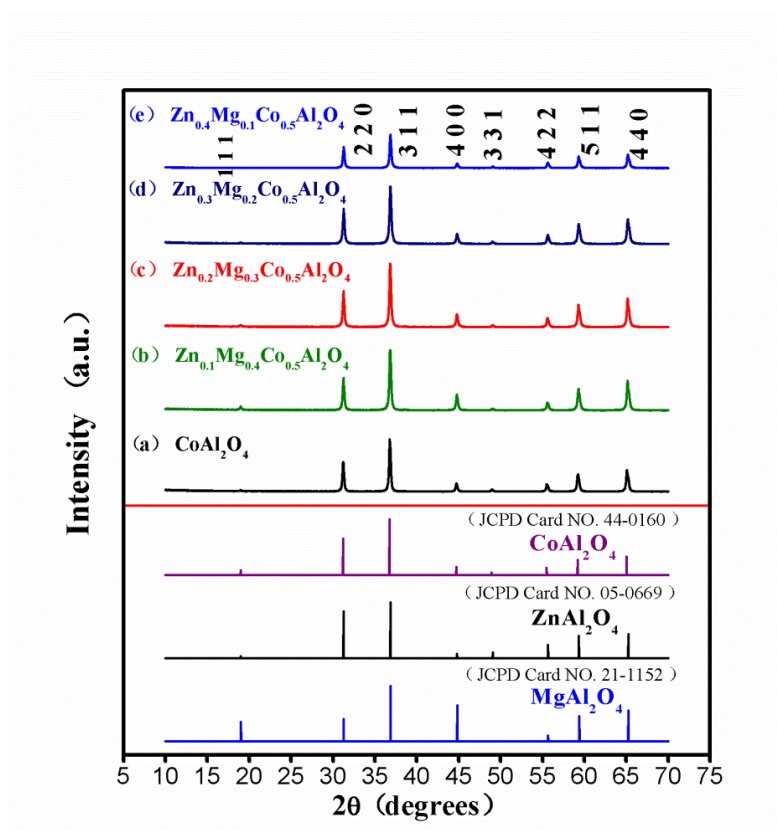


Fig. 3

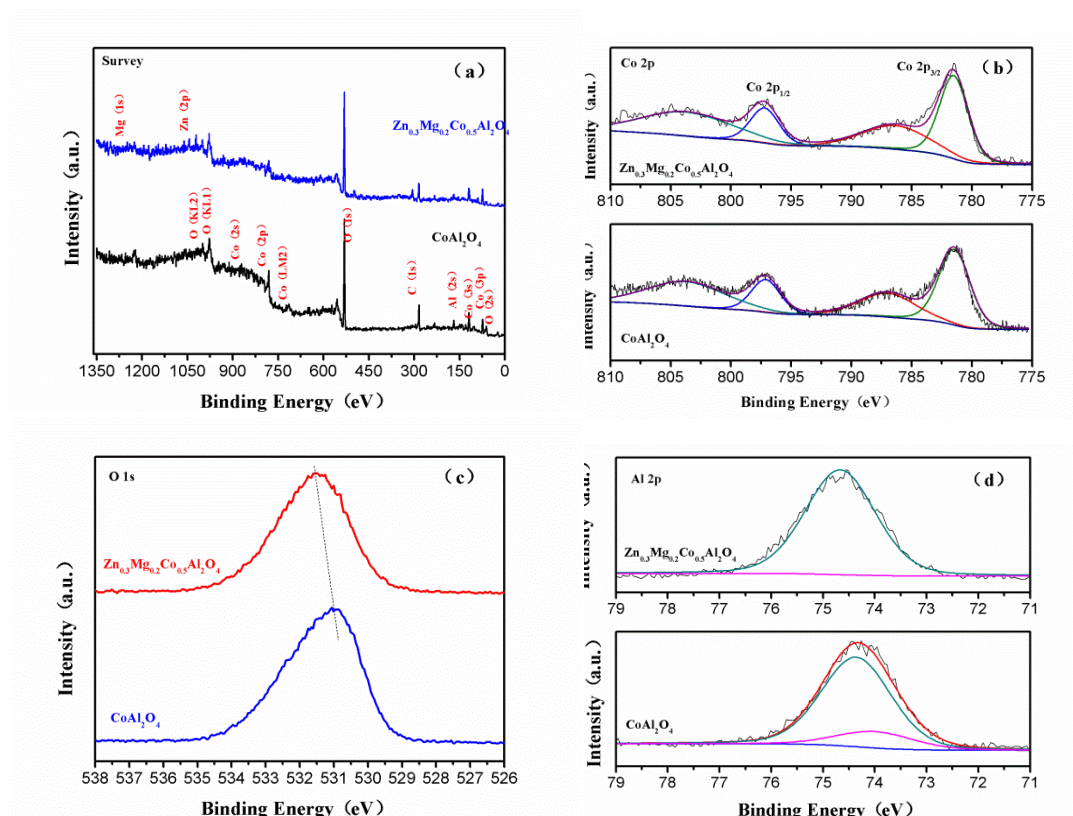


Fig. 4

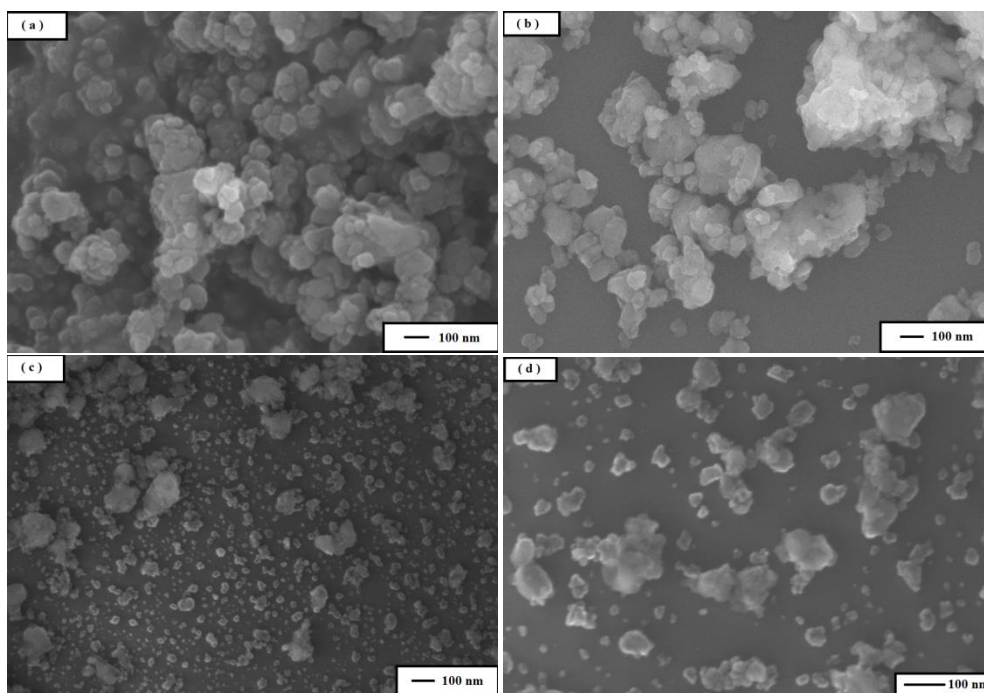


Fig. 5

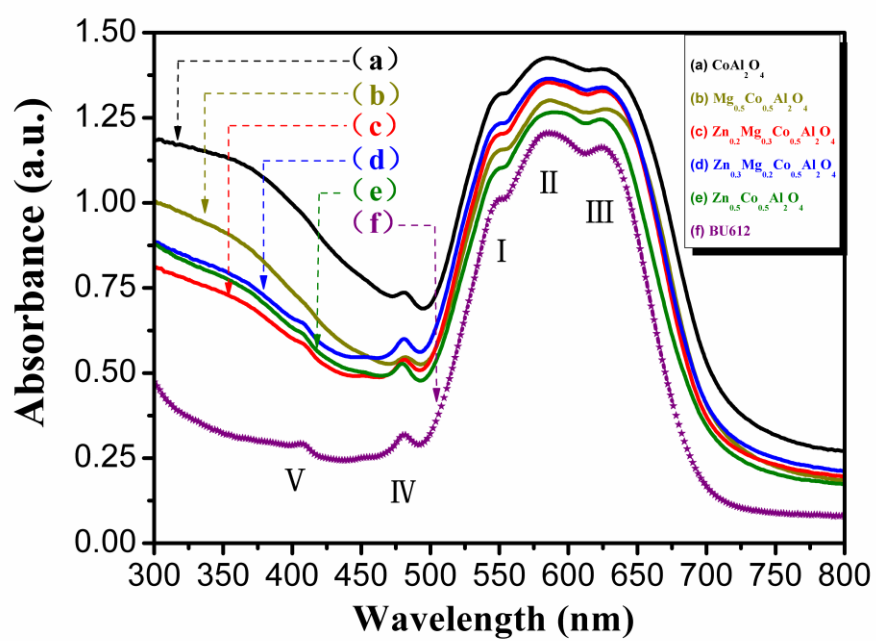


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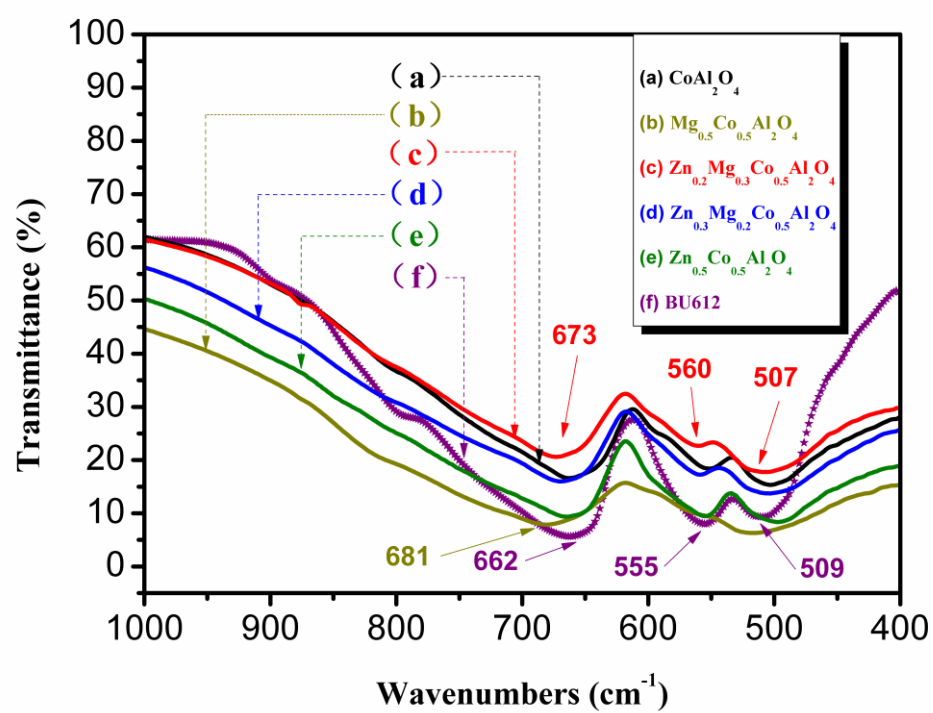


Fig. 7

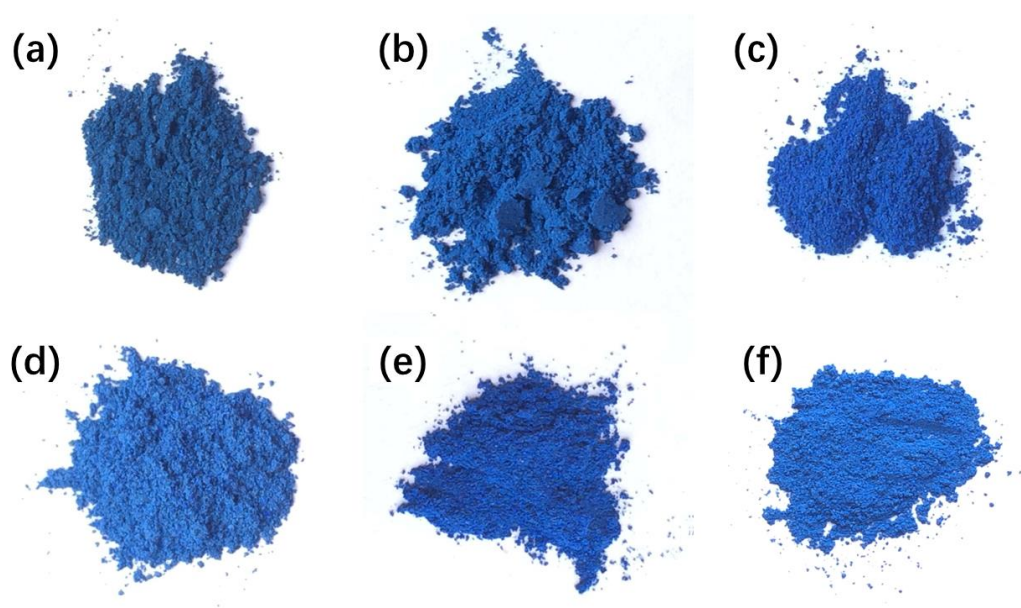


Fig. 8

Table captions:

Table 1 The particle size from XRD results and CIE-L*a*b* values of synthetic CoAl_2O_4 and $\text{Zn}_x\text{Mg}_{0.5-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$ ($x = 0, 0.1, 0.2, 0.3, 0.4, 0.5$) solid solutions nanocrystals as well as commercial CoAl_2O_4 pigment (BU612).

Tables :

Table 1

	X	Y	$\text{Zn}_x\text{Mg}_{1-x}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	Crystallite size (± 0.5 nm)	L*	a*	b*
ZM1			CoAl_2O_4	43	29.47	-12.44	-24.51
ZM2	0	0.5	$\text{Mg}_{0.5}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	42	33.26	-9.6	-25.44
ZM3	0.1	0.4	$\text{Zn}_{0.1}\text{Mg}_{0.4}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	40	33.75	-7.24	-26.57
ZM4	0.2	0.3	$\text{Zn}_{0.2}\text{Mg}_{0.3}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	41	34.62	-8.31	-28.03
ZM5	0.3	0.2	$\text{Zn}_{0.3}\text{Mg}_{0.2}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	39	35.82	-6.97	-28.27
ZM6	0.4	0.1	$\text{Zn}_{0.4}\text{Mg}_{0.1}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	43	36.04	-7.35	-27.98
ZM7	0.5	0	$\text{Zn}_{0.5}\text{Co}_{0.5}\text{Al}_2\text{O}_4$	42	44.88	-8.49	-25.37
BU612			CoAl_2O_4		36.09	-11.25	-28.47



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Environmental blue CoAl_2O_4 pigment co-doped by Zn^{2+} and Mg^{2+} : synthesis, structure and optical properties

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2017-12-09

Taylor & Francis

<http://dx.doi.org/10.1080/17436753.2017.1410941>

Peng X, Cheng J, Yuan J, Jin N, Kang J, Hou Y, Qi Z, Environmental blue CoAl_2O_4 pigment co-doped by Zn^{2+} and Mg^{2+} : synthesis, structure and optical properties, *Advances in Applied Ceramics*, Volume 117, 2018, Issue 5, pp. 303-311