Effective synthesis route for red-brown pigments based on Ce – Pr – Fe – O and their potential application for near infrared reflective surface coating

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Abstract. New cerium-based ceramic pigments, displaying $\text{Ce}_2\text{Pr}_{0.2}\text{Fe}_x\text{O}_{4.3+y}$ stoichiometry, were obtained at low temperature using a sol–gel method. The powder precursor dissolved in 80% ethylene glycol was precipitated using ammonia and the obtained gel calcined at 800°C for 2 h to yield homogeneous and crystalline particles with a diameter of around 150 nm. The oxide was composed of cerium in its +4 oxidation state and Pr in its +3 oxidation state. The oxides with varying Fe content had an intense red-brown colour, with bandgap energy of around 2.2 eV at 0.1 mol% Fe doping. The near infra red reflectance from these pigments, a measure of their ability to reflect rather than absorb heat waves from sunlight was found to be 82.7%, even in the absence of a white reflective base. Such high near infra red reflectance from these pigments qualify them for being ideal cool pigments for surface coating applications.

Keywords. Sol–gel route; calcination; rare earth pigments; benign colorants; red hue; bandgap energy; spectroscopy; NIR reflectance; cool colorants; magnetic coating.

1. Introduction

Inorganic pigments offer advantages such as heat and light stability, over their organic counterparts. However, the conventional solid state calcination approach to the preparation of these pigments result in larger size and uncontrolled morphology, thus affecting their optical purity. High temperature calcination also affects quality and performance parameters such as wettability of the powder, ability to adsorb oil alkyds, thermal and chemical stability, etc.^{1–4} Nano-sized pigments are slowly gaining market prominence due to performance features which are far superior to conventional pigments. For instance, scattering from a pigment coated surface is influenced by the surface area of pigment and number of air to pigment interfaces.⁵ Spherical, more so anisotropic nanoparticles, would have higher number of reflectance points and hence improved scattering.^{6,7} Further, paint formulations with smaller particle size pigments would allow homogeneous dispersion when mixed with the binder, leading to higher mechanical strength of the paint on drying.⁸ Nano-sized pigments have been synthesized through alternative soft chemical approaches with facile

and flexible chemistry.^{9,10} Amongst the soft chemical approaches, the sol–gel method is particularly attractive. High level of homogeneity and specific surface area can be obtained at much lower temperatures than the calcination method.¹¹ Sol–gel synthesis is generally carried out through two methods, viz., alkoxide gel and polymeric gel. In alkoxide gel method, hydrolysis of chloride precursor results in *in situ* formation of alkoxides,¹² while in the polymeric gel method, α -hydroxycarboxylic acids such as citric acid is employed as chelating agent, resulting in the formation of polybasic acid chelates of the metal cations as a transparent gel.¹³ Calcination of the citrate gel leads to nano-sized powders.^{14,15}

An analysis of the colour range of inorganic pigments reveals that the colours yellow, orange, red and maroon are always insufficiently represented for colouring of plastics, paints and ceramics and could comprise of toxic metal ions like Cd, Cr, and Pb. For instance, the conventional inorganic red pigment is either iron oxide or cadmium sulphoselenide encapsulated in zircon or oxide matrices.^{16,17} Inner orbital f–f transitions, wherein the electrons are shielded by the 5s and 5p electrons, provides for optically pure brilliant colours.^{18–21} Since 1990, lighter rare earths such as the lanthanides, whose global production as of 2007

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was 102.8 Gg,²² has shown tremendous potential as a functional material. The added advantage of the lanthanide group of elements is that dissolution, which serves as a marker for the evaluation of toxicity of metal ions is very low, mostly in the order of ppb.²³ Current knowledge, from public domain on the range of rare earth compounds for colouring applications is limited to sesquisulphides and oxides of cerium in association with other rare earth and transition metal ions and oxynitrides.^{24–26} For instance, sulphides of Ce^{3+} ($4f^1 5d^0$) ions such as $\gamma\text{-Ce}_2\text{S}_3$ and its alkali-metal derivatives $\gamma\text{-Ce}_{2-x}\text{A}_x\text{S}_3$ (A = alkali), doped ceria pigment (Pr, Tb, Eu), perovskites of the type CaTaO_2N and LaTaO_2N , etc. have been reported with a red hue.^{27–31} Disadvantages of such methods could be those relating to cost, need for high calcination temperatures, release of toxic gases, etc.

In this paper an attempt has been made to prepare red-brown pigments through the sol–gel route with advantages such as the ability to prepare homogeneous oxides of lower size which could provide for higher surface coverage. A survey of the literature on the Web of ScienceTM, for Ce–Pr oxide pigments provided for nine results, whose salient features are listed in table 1. It can be seen that doping of Pr into the cerium lattice brings about shift in absorption edge towards the lower energy or higher energy side, depending on the concentration of Pr or co-dopant employed. While different methodologies have been evaluated, no systematic study has been carried out employing sol–gel synthesis, where feasibility to optimize performance is easy through modulations in the steps involving preparation of sol, gelation and subsequent heat treatment for obtaining powders.³²

2. Experimental

The scope of this work was to synthesize Pr and Fe doped ceria through a sol–gel–calcination route so as to obtain oxide pigment with a red hue.

Reagents: All reagents used in this study were of ACS grade. Cerium(III) chloride hexahydrate, Praseodymium(III) chloride and Iron(III) chloride was sourced from M/s Aldrich chemicals, USA. Other minor chemicals employed in this study were procured locally.

2.1 Synthesis of Ce–Pr–O and Ce–Pr–Fe–O

Pure and Fe-doped cerium praseodymium oxides were synthesized from the corresponding chloride precursors. A homogeneous solution of the precursor chloride salts in 80% ethylene glycol was obtained by constant stirring (50°C, 300 rpm). To this homogeneous solution, 25 ml of 3.0 M ammonium hydroxide solution was added and stirring continued till the initial turbid red-yellow colour changed to red. Ageing of the solution for 10 h resulted in a gel-like material. Obtained gel was centrifuged (5000 rpm, 10 min) and washed thrice with milli-Q H_2O and finally with ethanol. The material free of unreacted impurities was air dried at 100°C for 24 h and subsequently calcined in a small electrically heated furnace at a temperature of 800°C for 2 h.

2.2 Characterization of the synthesized pigment

Size: Number average diameter of the synthesized pigment was determined through dynamic light scattering (DLS) measurement, performed on a Zetasizer nanoseries, using a He–Ne laser (633 nm), at a scattering angle of 173°. All measurements were carried out in triplicates after dispersing the pigment particles in water under sonication for 5 min. Diameter was computed using the software provided by the manufacturer and employing NNLS analysis.

Crystallinity and crystal size: Powder X-ray diffraction measurements were carried out using a Rigaku Multiflex instrument using a Ni filtered $\text{CuK}\alpha$ ($\lambda = 0.154060$ nm), a scintillation counter detector in the 2θ angle range of 10°–80° with step size of 0.1°. XRD patterns obtained were compared against standard data

Table 1. Analysis of the literature pertaining to praseodymium doped ceria for red coloured oxides.

Oxide	Colour	Preparation method	Remarks/reference
$\text{Ce}_{1-x}\text{Pr}_x\text{O}_2$	Red-orange	Flux	5 mol% Pr; ⁵⁵
Pr doped Ce hydrocarbonate	Red	Thermal decomposition	⁵⁶
Pr doped Ce	Red	Pyrolysis	Pr:Ce 0.091; ⁵⁷
$\text{CeO}_2\text{--Fe}_2\text{O}_3\text{--Pr}_6\text{O}_{11}$	Red-brown	Calcination	High temperature; ²¹
$\text{Ce}_{1-x}\text{Pr}_x\text{O}_2$	Red	Combustion	⁵⁸
$\text{Ce}_{0.9}\text{Pr}_{0.1}\text{O}_x$		Self propagation RT	⁵⁹
Ce–Ti–Pr		Solvothermal	⁶⁰
$\text{Ce}_{0.95}\text{Pr}_{0.05-x}\text{M}_x\text{O}_2$, M is Mn, Si	Red	Calcination	⁶¹

available with Powder Diffraction File-International Center for Diffraction Data (PDF-ICDD). The average crystal size of the synthesized pigment was calculated from the width of the reflection, by employing the Debye Scherer formula $D = 0.9\lambda/\beta \cos\theta$, where λ is the wavelength of the X-ray radiation, β is the full width at half maximum of the peak, θ is the angle of diffraction.

Morphology, size and elemental composition:

Scanning electron microscopic measurements were performed on JEOL JSM 5600-LV microscope with an accelerating voltage of 20 kV. The quantitative micro-analysis of the products was carried out by energy dispersive spectrometer (EDX, USA) attached to the SEM.

2.3 Reflectance spectra, colour coordinates

UV-vis diffuse reflectance spectra (UV-vis DRS) were obtained using a Shimadzu UV-2450 double beam spectrophotometer equipped with an integrating sphere attachment (ISR 2200). UVPC colour analysis personal spectroscopy software (version 3) was employed for obtaining the colour coordinates. For all the measurements, barium sulphate was employed as the internal white standard. The indirect bandgap energy was computed from the reflectance spectra, by employing the Kubelka–Munk formula $kh\nu = A(h\nu - E_g)^2$, which related the absorption coefficient k to frequency ν , through a constant A . A plot of $(kh\nu)^{1/2}$ against $h\nu$ provided the bandgap energy (E_g) when the linear fit of the plot is extrapolated to zero.³³

In the CIE $L^* a^* b^*$, 1976 system, a^* represents the axis red to green and b^* represents the axis yellow to blue. L^* represents the lightness or darkness of the colour as related to a neutral gray scale, with $L^* = 0$ indicating black and $L^* = 100$ indicating white. C^* indicates saturation of the colour and is calculated using the formula: $C = \sqrt{a^2 + b^2}$. The hue angle H° is defined by an angular position in the cylindrical colour space for instance, where H° ranging from 0 to 35° indicates red, and 35 to 70° orange colours. ΔE , the colour difference was computed as

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}.$$

2.4 Near infrared spectra and other characteristics

With polytetrafluoroethylene as standard, the relative reflectance, defined as the ratio of flux reflected by the specimen to that of the reference was measured using a Shimadzu UV-3600 UV-vis-NIR

spectrophotometer along with a diffuse reflectance accessory in the wavelength region of 700–2500 nm. NIR solar reflectance (R^*) was calculated in accordance with ASTM standard E891-87 as described elsewhere, though the same has been replaced with newer methods such as ASTM G173-03, as the E891-87 method was considered more prominent for spectrophotometer and reflectometer based calculation of solar reflectance.³⁴ Solar reflectance or fraction of solar radiation incident at wavelengths between 700–2500 nm is the irradiance weighted average of spectral reflectance, $r(\lambda)$, determined as

$$R^* = \frac{\int_{700}^{2500} r(\lambda)i(\lambda)d(\lambda)}{\int_{700}^{2500} i(\lambda)d(\lambda)},$$

where $r(\lambda)$ is the spectral reflectance (Wm^{-2}) obtained from the experiment and $i(\lambda)$ is the solar spectral irradiance ($\text{Wm}^{-2}\text{nm}^{-1}$) obtained from ASTM standard E891-87.

Oxidation state of metal ions involved: X-ray Photon electron spectroscopy measurements were carried out on a Omicron ESCA probe spectrometer equipped with monochromized Al-K α X-rays ($h\nu = 1486.6$ eV). Peak position calibration was performed using a silver metallic plate which had a 3d_{5/2} peak at 368 eV.

Magnetic properties of pigments: EG and G Princeton Applied Research Vibrating sample magnetometer 4500 was employed to study the magnetic properties of the synthesized pigments at a maximum applied field of 550 kA/m at room temperature.

Mass tone of the pigments: The ability of the pigments to disperse well into long oil alkyd medium and function as a constituent of surface coatings was evaluated by the conventional determination of mass tone as per procedure detailed in our earlier work.³⁵ Acid and alkali resistance of the pigment was evaluated by earlier reported method.⁴ The Fe content in the washing was evaluated further using inductively coupled plasma analysis performed using Perkin Elmer Optima 5300 DV ICP-OES. The water soluble matter in the pigment was determined using ASTM D1208 method. Thermogravimetric analysis was performed using Thermo Gravimetric Analyzer (TGA) – Model Q50 of M/s TA Instruments. TGA measurements were run in platinum crucible from 50°C to 800°C with a heating rate of 20°C/min in nitrogen atmosphere.

2.5 Application studies

Application studies were carried on automobile upholstery leathers. For this the synthesized pigment

Figure 1. X-ray diffraction patterns of Ce-Pr-Fe-O (a) Ce:Pr [2:0.2], (b) Ce:Pr: Fe [2:0.2:0.05], (c) Ce:Pr:Fe [2:0.2:0.1], (d) Ce:Pr:Fe [2:0.2:0.15], (e) Ce:Pr:Fe [2:0.2:0.2].

was used as a replacement for commercial pigment employed in a standard finish formulation. In short, desired quantity of pigment was dispersed in water in the presence of ammonia, following which 100 parts of the dispersed pigment was mixed with 200 parts of resin binder, 100 parts of protein binder, 50 parts of wax emulsion, 25 parts of a filler and 50 parts of a penetrator (all of which were commercial products). Four cross coats of season was sprayed on the leather. The season coat was fixed by lacquer emulsion.

3. Results and discussion

3.1 Crystalline character

Powder X-ray diffraction pattern of the Fe doped/undoped samples were characterized by intense sharp peaks corresponding to the (111), (200), (220), (311), (222) and (400) reflection lines (figure 1). These lines matched with that of cubic fluorite structure of CeO_2 ($Fm3m$ space group, $a = 5.411 \text{ \AA}$), in accordance with PDF-ICDD 000-034-0394.³⁶ A shift in diffraction peaks to lower angle side observed in this study is an indication of the incorporation of Fe^{3+} into the matrix, which was further confirmed by increase in the unit cell parameter. Unit cell parameter for the stoichiometric formula $\text{Ce}_2\text{Pr}_{0.2}\text{Fe}_x\text{O}_{4.3+y}$, where X was 0, 0.05, 0.1, 0.15 and 0.2, calculated as an average of all planes was determined as 5.386 $\text{\AA}$, 5.414 $\text{\AA}$, 5.411 $\text{\AA}$, 5.413 $\text{\AA}$ and 5.411 $\text{\AA}$, respectively. The increase in unit cell parameter could be attributed to the increase in volume of elements in each unit cell. In all the XRD patterns, secondary phases were characteristically absent, indicating substitution of Ce^{4+} in the CeO_2 lattice by Fe/Pr. Crystal size calculated from the (220) reflection was found to be 36.12, 30.96, 28.44, 27.09 and 27.90 nm for $X = 0, 0.05, 0.1, 0.15$ and 0.2 in the pigment composition $\text{Ce}_2\text{Pr}_{0.2}\text{Fe}_x\text{O}_{4.3+y}$. A decrease in crystallite size with increasing Fe content could be attributed to the broadening of the peaks. This is probably due to the fact that smaller Fe^{3+} ions enter into the larger ceria lattice.³⁷

Figure 2. SEM EDX micrograph of Ce-Pr-Fe-O (0.1 mol% Fe).

Figure 3. XPS spectra of Ce–Pr–Fe–O (0.1 mol% Fe).

3.2 Morphology and elemental composition

SEM of 0.1 mol% Fe doped sample (figure 2) did not show any pronounced aggregation. Particle size was determined to be in the range of 29–31 nm through instrument based calibrated systems. From EDAX measurements, the atomic weight composition was found to be 29.69% Ce, 6.64% Pr, 2.11% Fe and 58.17% O. This elemental composition matches well with the stoichiometric ratio expected for the synthesized oxide, based on the mol ratios of the starting materials adopted.

3.3 Oxidation state of metal ions involved

XPS spectra of Ce–Pr–O sample showed two sets of spin orbit multiplet at binding energy 884.6 and

902.7 eV corresponding to $3d_{5/2}$ and $3d_{3/2}$ levels with energy spacing of 16 eV (figure 3).^{38,39} This clearly indicated that cerium was in +4 oxidation state. The Pr3d spectra consisted of two sets of spin orbit multiplets at binding energy 933.57 and 954.14 eV, corresponding to $3d_{5/2}$ and $3d_{3/2}$ levels with energy spacing of 20.5 eV, indicating praseodymium to be in +3 state.⁴⁰ XPS profile of O1 in Ce–Pr–Fe oxide sample had main feature at 529.4 eV, which could be attributed to lattice oxygen associated with Ce–Pr oxide. XPS spectra of 0.1 mol% Fe doped sample showed a peak at 713 eV,^{41,42} indicating the presence of Fe in its +3 oxidation state.

3.4 Particle size

As the synthesized oxide without Fe doping was only moderately dispersible in water, the dynamic light scattering technique indicated a higher number average

Figure 4. Reflectance spectra with bandgap energy in inset of Ce–Pr–Fe–O (a) Ce:Pr [2:0.2], (b) Ce:Pr:Fe [2:0.2:0.05], (c) Ce:Pr:Fe [2:0.2:0.1], (d) Ce:Pr:Fe [2:0.2:0.15], (e) Ce:Pr:Fe [2:0.2:0.2].

Figure 5. TGA curve of Ce:Pr:Fe [2:0.2:0.1].

Table 2. The Colour coordinates of Ce–Pr–Fe–O with varying Fe doping.

Composition	Colour coordinates					
	L^*	a^*	b^*	h^o	c	
Ce: Pr–2:0.2	45.03	10.56	10.75	45.53	15.07
Ce: Pr: Fe – 2:0.2: 0.05	39.26	16.93	14.93	41.42	22.57
Ce: Pr: Fe – 2:0.2:0.1	41.03	18.89	17.13	42.2	25.5
Ce: Pr: Fe – 2:0.2:0.15	41.73	17.14	17.06	44.86	24.19
Ce: Pr: Fe – 2:0.2:0.2	40.12	15.96	15.29	43.77	22.1

diameter of 213 nm, possibly due to particle clustering. Fe doping into the CeO₂ lattice brought about a decrease in size of the particles. The number average diameter of 0.2 mol% Fe doped sample was found to be 197 nm. This decrease in size when compared to that of undoped sample is expected to have led to the observed colour change on Fe doping.^{43,44}

3.5 Reflectance, bandgap and colour coordinates

Diffuse reflectance spectra of the oxide with/without Fe doping in the reflectance mode were characterized by intense reflectance from Ce–Pr–O (figure 4). Change in the bandgap (E_g) with Fe³⁺ doping is presented as an inset to figures 4. It can be seen that E_g value

of Ce–Pr–O drops drastically from 3.0 ± 0.02 eV to around 2.2 eV on doping with Fe³⁺. This reduction in bandgap can be attributed to the fact that Fe³⁺ induces a defect level within the band gap of the host lattice.⁴⁵ This value is much closer to a comparative red pigment – vermilion (HgS) with a bandgap of 2.1 eV, compared to Pr doped TiCeO₄ (1.84 eV) or Zr/Sn doped Ce–Pr–O (3.06 eV). Incidentally, a similar approach adopted by Nunes *et al.* also yielded oxides with higher bandgap energies (2.6–3.08 eV), probably because of the higher loading of Fe (20–95 wt%).⁴⁶

The variation in a^* and b^* values with increasing mol% Fe doping is presented in table 2. Colour coordinates matching closely to that reported elsewhere⁴⁶ was obtained at 0.1 mol% Fe doping.

Table 3. Colour coordinates of the pigment after acid and alkali wash.

Samples Ce:Pr:Fe [2:0.2:0.1]	Colour coordinates					ΔE
	L^*	a^*	b^*	h^o	c	
Before washing	41.03	18.89	17.13	42.2	25.5	–
Acid washed	42.18	17.08	18.01	41.42	22.10	2.27
Alkali washed	43.45	18.98	17.37	39.41	21.62	2.42

Figure 6. NIR Solar reflectance spectra of Ce–Pr–Fe–O (a) Ce:Pr [2:0.2], (b) Ce:Pr:Fe [2:0.2:0.1].

3.6 Application as a pigment for surface coating

For any industrial application as pigment intended for surface coating applications, the pigments are expected to have acid and alkali resistance. The colour difference of the developed oxide with 0.1 mol% Fe doping (table 3) before and after acid/alkali washing was less than 2.5. It is generally considered that ΔE values between 2 and 3 indicate medium colour difference perceptible to even an untrained eye. However, such values are dependent on parameters such as nature of colour and method employed for determination of acid stability, with values up to 5 reported as acceptable.⁴⁷ The iron content in leached out after acid/alkali washing was estimated as 0.2 wt% and 0.18 wt% pigment,

respectively. The water soluble matter in the pigment was 0.74%, which was higher than that reported for iron oxide pigments of similar hue (IS 44:1991). Visual assessment of the resistance to bleeding in water, mineral turpentine, isopropyl alcohol, methanol and ethanol as determined by experts in the field was rated as excellent (10 out of 10). Thermal stability of the pigment with 0.1 mol% Fe doping was determined by measuring the weight loss of the pigment under pre-defined conditions in a thermogravimetric analyser (figure 5). It was observed that the maximum loss of weight from the pigment was less than 2% at a temperature of 800°C, and below 0.5% at temperatures up to 300°C, indicating that the pigments could be employed for high temperature applications such as those in ceramics and plastics.

3.7 As a cool pigment

Interest in pigments that could contribute to energy savings by way of reduced demand on cooling is increasing day-by-day.^{48,49} Such pigments have an ability to reflect a larger part of the solar radiation which falls in the near infrared region.⁵⁰ From the NIR spectra presented in figure 6, NIR solar reflectance (R^*) was calculated as 57% for the Ce–Pr–O and 82.7% for the sample with 0.1 mol% Fe doping. These values were much higher than that reported (39%) for commercial infrared reflective red-brown pigment (V-13810 red).⁵¹ Our research and those from other groups indicate that an increase of R^* value should be attributed both to the presence of rare earth metal ions and the size of the pigment.^{52,53} The increase in NIR reflectance by 26% in the case of

Table 4. Colour coordinates and ΔE for red pigment on a coated card.

Composition	Colour coordinates					ΔE
	L^*	a^*	b^*	h^o	C^*	
Ce: Pr (2:0.2)						
Black	39.49	11.89	11.98	45.22	16.88	3.99
White	36.47	14.22	13.22	42.90	19.42	
Ce: Pr: Fe (2:0.2:0.1)						
Black	42.09	16.50	11.32	34.46	20.01	0.23
White	42.26	16.66	11.37	34.32	20.18	

Table 5. Colour coordinates of Ce–Pr–Fe – O (t 0.1 mol% Fe) coated through a formulation on leather surface at different points on the leather.

Point	Colour coordinates				
	L^*	a^*	b^*	h^o	c
1	42.13	10.13	9.55	13.92	43.30
2	41.68	10.28	9.25	13.83	41.98
3	41.19	10.34	10.18	14.51	44.54

Figure 7. VSM of Ce–Pr–Fe–O (a) Ce:Pr [2:0.2], (b) Ce:Pr:Fe [2:0.2:0.1].

the Fe doped sample should be attributed to the decrease in size by about 16 nm. Such high values for reflectance have been reported earlier only in the presence of a reflective basecoat such as TiO_2 .⁵⁴

A paint formulation developed using the pigment (0.1 mol% Fe doped) was evaluated for its mass tone and hiding power, at a coating thickness of 24 microns. It can be seen from table 4 that in the presence of Fe doping, the covering power of the pigment improved drastically, as indicated by the ΔE value between the coated black region and the white region.

3.8 As a colorant for leather

The pigment (0.1 mol% Fe doped) was easily dispersible in water in the presence of ammonia. The formulation consisting of pigment and binders also had good flow properties, which permitted the easy spraying of the same on to leather. Four cross coats of season was sprayed on the leather. The season coat was fixed by lacquer emulsion. The film formed was fast to dry and wet rub. The colour was also uniform, as indicated by the CIELAB coordinates (table 5).

3.9 Magnetic properties of the pigment

The magnetization curves obtained from room temperature VSM measurements are shown in figure 7. In the presence of 0.1 mol% Fe, a ferromagnetic behaviour with saturation magnetization value (M_s) of 0.31 emu/g as against 63.6×10^{-3} emu/g for undoped sample was observed. Coercivity value of 142 Oe matched well with standard magnetic pigments.

4. Conclusions

A sol–gel–calcination approach for the synthesis of pigments with a red hue based on Ce–Pr–Fe–O was developed. The pigment was characterized by a cubic fluorite structure of CeO_2 , with no secondary peaks

observed for Pr or Fe oxide. From the XPS spectra, for a 0.1 mol% Fe doped oxide, the oxidation state of Ce was determined as 4+ and that of Pr and Fe as 3+. Doping of Fe into the CeO_2 lattice brought about a reduction in size of the oxide, which in turn contributed to the red-brown hue and increased solar reflectance of 26% over Ce–Pr–O. The oxide was characterized by low water soluble matter and high level of acid/alkali resistance, making it an ideal candidate for surface coating applications. Paint and finish formulation developed based on the pigment had good covering properties.

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