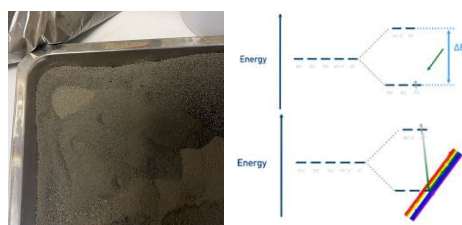


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Introduction

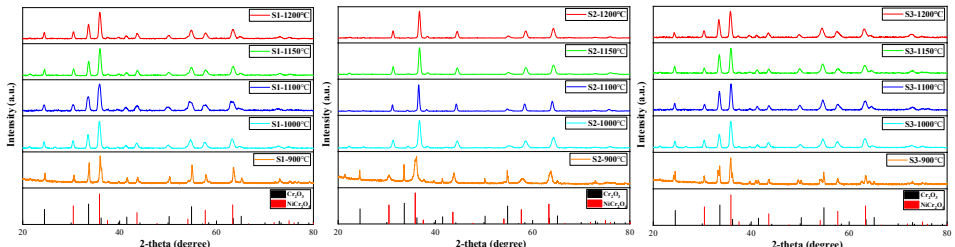
Electroplating processes generate large amounts of sludge containing transition-metal elements such as Cr, Ni, Zn, and Fe. Conventional treatment mainly relies on stabilization and landfilling, which not only consumes landfill capacity but also fails to recover the potential value of these metal resources. Therefore, converting electroplating sludge into value-added products represents a promising strategy for waste reduction and resource recycling. Inorganic mineral pigments are particularly attractive because transition-metal elements can act as chromophores and may form thermally and chemically stable crystalline phases during sintering. According to previous studies, electron-pinned defect dipoles (EPDD) can be utilized to achieve both colossal permittivity and low dielectric loss.

The color of transition-metal-based pigments is closely related to their electronic configuration and crystalline environment. The 3d electrons of transition-metal ions can undergo d-d electronic transitions, resulting in selective absorption of visible light. Consequently, variations in elemental composition, oxidation state, and crystalline phase can lead to significant changes in pigment color. Previous studies on electroplating-sludge-derived pigments have mainly focused on black pigments, while systematic control of color diversity and color stability remains limited.



This study aims to investigate the effects of composition and sintering temperature on crystalline phase formation, optical absorption, and color characteristics of inorganic pigments derived from electroplating sludge.

XRD



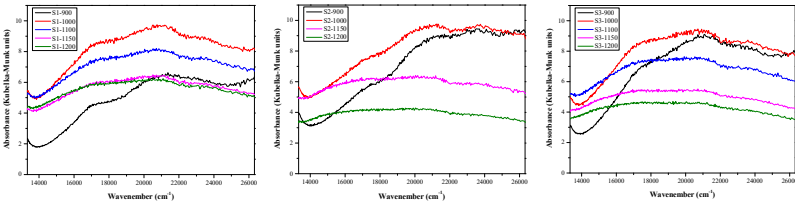
- The diffraction peaks of the sintered samples were mainly associated with Cr₂O₃ and NiCr₂O₄, indicating the development of chromium-containing crystalline phases during sintering.
- With increasing sintering temperature from 900 to 1200 °C, the diffraction peaks generally became sharper and more distinct, suggesting enhanced crystallinity and phase development.
- Although the major phase assemblages remained similar within each formulation, the relative peak intensities varied with temperature, indicating changes in the relative phase contribution and crystallization behavior.
- Different Fe–Cr–Ni compositions produced distinct diffraction patterns, demonstrating that composition strongly influences phase evolution during sintering.

Color Properties Characterization

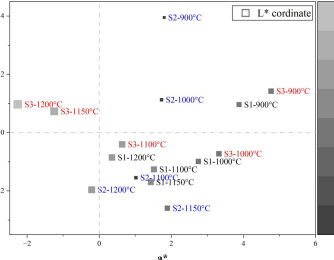
CIE L*a*b* Color Analysis

Fe:Cr:Ni	Temperature (°C)	L*			a*	b*
		0 (Black) to 100 (White)			(+Red, -Green)	(+Yellow, -Blue)
S1 (Standard Brown-Black) 1:2:1	900	32.81	3.88	0.96		
	1000	33.48	2.75	-0.99		
	1100	35.04	1.52	-1.26		
	1150	34.63	1.43	-1.70		
	1200	36.19	0.36	-0.85		
S2 (Enhanced Blue-Gray) 1:2:2	900	27.59	1.81	3.95		
	1000	28.86	1.73	1.12		
	1100	29.11	1.02	-1.55		
	1200	33.23	1.89	-2.59		
S3 (Stable Brown) 2:2:1	900	37.26	-0.21	-1.96		
	1000	33.82	4.77	1.42		
	1100	33.66	3.32	-0.73		
	1200	36.26	0.64	-0.40		

UV-Vis-NIR Spectroscopy (Visible Region)



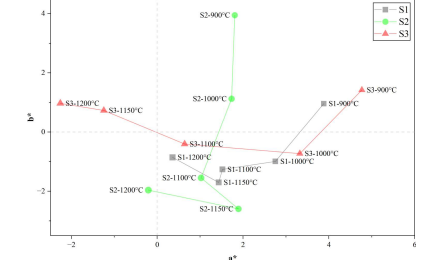
Color Distribution and Lightness



- Temperature mainly increased lightness, whereas Fe–Cr–Ni composition determined the direction of hue evolution.
- Samples shifted toward different regions in the a*–b* color space depending on the Fe–Cr–Ni composition.

The distinct color trajectories correspond to composition-dependent redistribution of visible-light absorption, indicating that hue is controlled by the relative spectral response rather than absolute absorption intensity.

Composition-Dependent Color Evolution



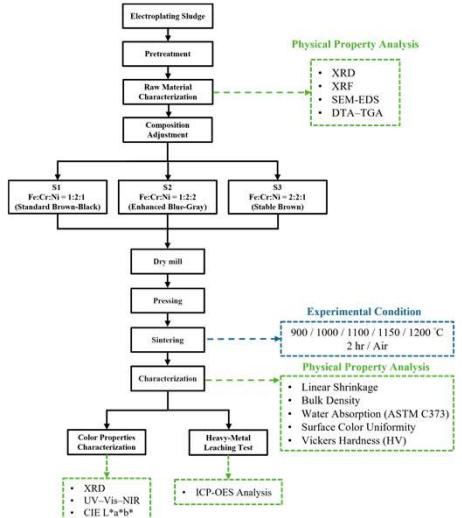
- S1: Gradually shifted from reddish-brown toward a more neutral, slightly blue-gray region.
- S2: Exhibited a pronounced yellow-to-blue shift between 1000 and 1100 °C, reaching the strongest blue tendency at 1150 °C.
- S3: Approached neutral gray near 1100 °C, then shifted toward the green-yellow region at higher temperatures.

- Fe–Cr–Ni composition strongly governs the visible-light absorption profile, demonstrating composition-dependent optical responses among S1–S3.
- All formulations exhibited a pronounced optical response near 1000°C, indicating a critical stage in the evolution of the transition-metal oxide system.
- Color evolution is governed by the redistribution of broad visible-light absorption rather than absolute Kubelka–Munk intensity, producing distinct hue pathways for the Ni-rich and Fe-rich formulations.

Conclusion

- Cr₂O₃ and NiCr₂O₄ were identified as the major crystalline phases after sintering.
- Pigment color can be tailored by controlling Fe–Cr–Ni composition and sintering temperature. S1 gradually approached a near-neutral color, while Ni-rich S2 exhibited a pronounced yellow-to-blue transition (b*:+3.95→–2.59), and Fe-rich S3 shifted from reddish-brown toward green-yellow (a*:+4.77→–2.26).
- UV–Vis analysis revealed that color evolution is associated with the redistribution of broad visible-light absorption rather than absolute absorption intensity. Sintering altered the optical response of the transition-metal oxide system, leading to distinct composition-dependent color trajectories.
- Electroplating sludge shows strong potential as a raw material for tunable inorganic pigments.

Experiment



Sample Characteristics

Raw Material Composition : XRF Analysis

Element	Cr	Fe	Ni	Cu	Al	P	S	Ca
Weight	12.34	13.48	39.38	9.41	7.77	6.73	4.41	1.81

Electroplating sludge is rich in Fe, Cr, and Ni, which can serve as coloring elements for inorganic pigments.

Color Appearance of Sintered Samples

Sample	900°C	1000°C	1100°C	1150°C	1200°C
S1					
S2					
S3					