A camouflage coating with similar solar spectrum reflectance to leaves based on polymeric inorganic composite

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Abstract
To realize the hyperspectral camouflage under the background of vegetation, a camouflage polyvinyl alcohol coating containing lithium chloride and green pigment particles of chromium sesquioxide (Cr2O3) was prepared on a stainless-steel substrate. Based on the four flux Kubelka-Munk model, the reflectances of the coatings with different volume fractions of Cr2O3 (fC) were predicted and compared with those of the membranes without substrate. The results show that when fC reaches 0.8%, the 0.2 mm thick coating can conceal the reflectance characteristics of the stainless-steel substrate. The reflectances of the coatings with the volume fraction of water (fW) in the range from 0% to 50% were also calculated via the model. It is found that the reflectances around 1460 nm and 1940 nm decrease with increased fW due to the significantly enhanced absorption coefficient, and the correlation coefficient between the spectral reflectances of the camouflage coating and an Osmanthus fragrans leaf increases from 0.913 to 0.954, indicating that the coating camouflage performance can be improved by increasing fW.

1. Introduction
Hyperspectral imaging can meet the general needs of ground object detection and is widely used in vegetation research, atmospheric and environmental remote sensing and camouflage recognition [1–3]. To achieve hyperspectral camouflage in the background of vegetation which is one of the common ground backgrounds, it is necessary to develop a camouflage material that can simulate the solar spectral reflectance characteristics of leaves.

Figure 1 shows the reflectances of several kinds of green leaves in the wavelength range from 300 nm to 2500 nm [4]. Four basic features in the reflectance spectra of the above leaves are found, i.e., ‘green peak’, ‘red edge’, ‘near-infrared plateau’ and water absorption bands. A broad noticeable reflectance peak, i.e., ‘green peak’, centered near 550 nm in the visible light region is mainly attributed to the absorption characteristics of chlorophyll [5, 6]. In the range from 680 nm to 780 nm, with the rapid decrease of the chlorophyll absorption coefficient, the multiple reflections of a loose and porous leaf cell structure rapidly dominate, consequently, the reflectance rises sharply to form the ‘red edge’ [7–9]. The ‘near-infrared plateau’ is located in the range from 780 nm to 1300 nm and the value of the reflectance in the range maintains at approximately 50%, which because the leaves contain no other substances that absorb strongly and the multiple reflections of the loose and porous leaf cell structure still dominate [7, 8]. Regarding the near-infrared region, two noticeable water absorption bands are located around 1460 nm and 1940 nm, respectively, associated with the absorption characteristics of the leaf water [10, 11].

The processes of the absorptions of leaf biochemical components and multiple reflections of the leaf cell determine the solar spectral reflectance characteristics of the leaves. The camouflage materials composed of the substances that can realize the above processes are expected to simulate the solar spectral reflectance characteristics of the leaves. According to this basic principle, some camouflage materials have been developed to counter hyperspectral detection in the solar spectrum region. Zhang et al. [12] prepared a camouflage cotton fabric by using
dyes with similar spectral properties to green leaves. The dyes and cotton fabric were used to simulate the chlorophyll absorption and the leaf cell multiple reflections, respectively. Consequently, the camouflage cotton fabric could approximately simulate the ‘green peak’, ‘red edge’ and ‘near-infrared plateau’ of the leaves. Whereas this material could not simulate the water absorption bands after 1300 nm because no water was accommodated.

To further simulate the spectra of leaves within 400 nm to 2500 nm, Yang et al. [13] encapsulated chlorophyll into polyvinyl alcohol (PVA) film, and composited with a sealed bag of polyvinylidene chloride containing water and a piece of paper to prepare a bionic leaf by simulating their composition and structure. The chlorophyll film and the sealed bag of water realized the processes of the absorptions of the leaf in the visible light and near-infrared regions, respectively. In addition, the paper with a porous structure was used to simulate the leaf cell structure. However, this bionic leaf is difficult to be applied in practice due to its complex multilayer structure as well as the preparation process. Qin et al. [14] prepared a microcapsule containing chlorophyll and water to simulate the absorptions of the leaf chlorophyll and leaf water in the visible light and near-infrared regions. Moreover, the scattering property of the microcapsule particle helped this camouflage material realize the process of multiple reflections to simulate the characteristics of the ‘red edge’ and ‘near-infrared plateau’ of the leaves. Chlorophyll was widely used in these camouflage materials to simulate the spectral reflectance features of green leaves in the visible light region, whereas its stability is poor and it is easy to decompose. Chromium sesquioxide, whose basic chemical formula is Cr$_2$O$_3$, is green in color and possesses a reflectance spectrum similar to that of chlorophyll [15]. Besides, due to its high stability, pronounced tinting strength, good migration resistance, and low cost [15–17], Cr$_2$O$_3$ has already been used in camouflage coating by armies for preventing from detection of objects purpose [18–20]. In our previous research, a bionic camouflage membrane composed of PVA as a resin matrix, anhydrous lithium chloride (LiCl) and particles of Cr$_2$O$_3$ as fillers was prepared [4, 21]. LiCl is highly hydrophilic and can absorb 7.9 g/g moisture at 25 °C and 95% relative humidity [22]. Furthermore, the scattering property of Cr$_2$O$_3$ also can realize the process of leaf cell multiple reflections. The results showed that the measured spectral reflectance of this bionic camouflage membrane was similar to that of the green leaf in the range from 300 nm to 2500 nm [4, 21]. It is worth noting that, the main function of the camouflage materials is to cover the spectral reflectance characteristics of a target substrate and to present the spectral reflectance characteristics similar to the leaves. In our previous work, four flux Kubelka-Munk (K-M) model was used to predict the reflectance and transmittance of the camouflage membrane [4]. The results showed that the 3 mm thick camouflage membrane containing the volume fraction of Cr$_2$O$_3$ equal to 1.61% was almost opaque in the range from 300 nm to 2500 nm, indicating that this camouflage membrane was theoretically capable of concealing the spectral reflectance characteristics of the target substrate underneath. Whereas, if the thickness of the camouflage material is insufficient, the material will be translucent, and its spectral reflectance will be affected by the optical constants of the substrate underneath. At present, the researches of the reflection mechanism and camouflage performance optimization of a camouflage coating on a metal target considering the practical application have rarely been discussed.

![Figure 1. Solar spectral reflectances of several kinds of green leaves. Reprinted from [4], Copyright (2017), with permission from Elsevier.](image-url)
The purpose of this study was to determine the effects of Cr$_2$O$_3$ content and water content on the spectral reflectance in the camouflage coating coated on a stainless-steel substrate. In this work, the four flux K-M model of the camouflage coating was established. Based on the model, the reflectances of the camouflage coating and camouflage membrane containing different Cr$_2$O$_3$ contents were calculated, and the variations of the collimated and diffuse reflectances of the above materials with Cr$_2$O$_3$ content were analyzed in detail. In addition, the reflectances of the camouflage coatings with different water contents were also predicted via the model. The objectives were: 1) to reveal the influence mechanism of Cr$_2$O$_3$ content on the reflectance characteristics of the camouflage coating and identify the Cr$_2$O$_3$ content that the coating could cover the reflectance characteristics of the stainless-steel substrate; 2) to reveal the influence mechanism of water content on the reflectance characteristics of the camouflage coating.

2. Experimental

2.1. Materials
PVA (batch number PVA 124, guaranteed reagent quality) was supplied by Sinopharm Chemical Reagent Co., Ltd (China). L-Malic acid of analytical reagent was used as a PVA crosslinker and supplied by J&K Chemical Ltd. Anhydrous lithium chloride of analytical reagent was supplied by Tianjin Fengchuan chemical reagent Technology Co., Ltd. Cr$_2$O$_3$ particles were supplied by Hua’an Pigment Co., Ltd.

2.2. Camouflage coating preparation
The camouflage coating was prepared by a solution casting method [23, 24]. Firstly, 9 g PVA was mixed with 91 g deionized water and stirred at 95 °C for 1.5 h to obtain a uniform PVA aqueous solution. Then, the temperature of the PVA aqueous solution was cooled to about 70 °C, and 4 g L-malic acid, 2 g anhydrous LiCl and 0.1 g Cr$_2$O$_3$ particles were added to form a uniform casting solution by stirring for about 0.5 h. After that, the casting solution was placed into an electric thermostatic drying oven (DHG-9070A) for cross-linking at 100 °C for 1 h. The cross-linked casting solution was coated on a stainless-steel substrate with the size of 30 mm × 40 mm × 1 mm and placed still at room temperature for approximately 24 h to form the camouflage coating through solvent evaporation.

2.3. Characterization
A spectrophotometer (Shimadzu DUV-3700) with an integrating sphere with a diameter of 60 mm coated with BaSO$_4$ was used to measure the directional-hemispherical reflectance of the camouflage coating in the spectral range from 300 nm to 2500 nm. As shown in figure 2, there are four ports with 2.2 cm × 1.1 cm in size of the integrating sphere, i.e., 0° and 8° light entrance ports and the corresponding light exit ports. An incident angle was set to 8° to determine the hemispherical-reflectance composed of the diffuse reflectance and collimated reflectance. A baseline calibration scan was first conducted, i.e., the BaSO$_4$ reference standard was used as a reference. After that, the sample was placed at an exit corresponding to light with an incident angle of 8°. The reflectance of the sample, $R_{\text{mes}}$, can be calculated by: 

![Figure 2. Schematic diagram of directional-hemispherical reflectance measurement of the sample.](image-url)
where $R_{\text{mes}}$ is the measured relative reflectance of the sample, $R_{\text{BaSO}_4}$ is the reflectance of the BaSO$_4$ reference standard, which has been corrected before taking the measurement and the corrected result is shown in figure 3. According to the calibration result, the uncertainty of the reflectance of the spectrophotometer is 1%.

3. Radiative transport model

3.1. Four flux K-M model

Assuming the uniform distribution of Cr$_2$O$_3$ particles, the propagation process of light in the camouflage coating can be described by the four flux K-M model. Figure 4 shows the transmission process of light in the camouflage coating with a thickness of $Z$. As shown in the left part of figure 4, when a beam of collimated light is incident upon the upper surface at $z = 0$ of the camouflage coating, a part of the incident collimated light is reflected by the interface between the air and the coating, and the rest penetrates into the interior of the coating.
After being absorbed and scattered for many times in the coating, the remaining part reaches the bottom surface at \( z = Z \) of the coating and is reflected by the interface between the coating and the stainless-steel substrate again. Finally, the rest goes into the interior of the stainless-steel substrate and is completely attenuated due to the strong absorption of the stainless-steel substrate. It is important to note that the collimated light scattered by the particles is converted into diffuse one which also undergoes multiple absorptions, scatterings and interface reflections. Consequently, as shown in the middle part of figure 4, there are four radiation fluxes in the interior of the coating. In our work, assuming that the incident direction of the collimated light was the positive direction, the downward and upward propagating collimated radiation fluxes were defined as \( q^+_{c,d} (z) \) and \( q^-_{c,d} (z) \), and the corresponding diffuse ones were defined as \( q^+_{c,d} (z) \) and \( q^-_{c,d} (z) \), respectively. The variations of the collimated and diffuse radiation fluxes in the coating with an infinitesimal thickness of \( dz \) can be described by the following equations [25]:

\[
\frac{dq^+_{c}}{dz} = -\zeta_c (k + F_s + B_s) q^+_{c} - dq^-_{c}/dz
\]

\[
-\frac{dq^-_{c}}{dz} = -\zeta_c (k + F_s + B_s) q^-_{c}
\]

\[
\frac{dq^+_{d}}{dz} = -\zeta_d (k + B_s) q^+_{d} + \zeta_d B_s q^-_{d}
+ \zeta_c F_s q^+_{c} + \zeta_c B_s q^-_{c}
\]

\[
-\frac{dq^-_{d}}{dz} = -\zeta_d (k + F_s + B_s) q^-_{d} + \zeta_d B_s q^+_{d}
+ \zeta_c F_s q^-_{c} + \zeta_c B_s q^+_{c}
\]

where \( \zeta_c \) and \( \zeta_d \) are the average path parameters of the collimated and diffuse lights, \( \zeta_c \approx 1 \) for the collimated light at normal incidence and \( \zeta_d \approx 2 \) for the isotropic diffuse light [26], respectively. \( k \) and \( s \) are the absorption and scattering coefficients, \( F \) and \( B \) are the forward and backward scattering coefficients of the particles, respectively. For the isotropic scattering, \( F \) and \( B \) are approximately equal to 0.5. As shown in the right part of figure 4, the boundary conditions of the above equations can be described as

\[
q^+_{c} (0) = (1 - r_c) I^{0}_c + r_c q^-_{c} (0)
\]

\[
q^-_{c} (Z) = r_c q^+_{c} (Z)
\]

\[
q^+_{d} (0) = r_d q^-_{d} (0)
\]

\[
q^-_{d} (Z) = r_d q^+_{d} (Z)
\]

where \( I^{0}_c \) is the radiation flux of the incident collimated light, \( r_c \) and \( r_{c,c} \) are the reflection factors at the interface between air and coating and the interface between the coating and stainless-steel substrate for the collimated light, respectively, \( r_d \) and \( r_{d,d} \) are those for the diffuse light. Based on the boundary conditions, the four radiation fluxes can be solved, and eventually, the total reflectance,

\[
R = R_c + R_d = (q^-_{c,r} + q^-_{d,r})/I^{0}_c
= [r_c I^{0}_c + (1 - r_c) q^-_{c} (0) + (1 - r_d) q^-_{d} (0)]/I^{0}_c
\]

where \( R_c \) and \( R_d \) are the collimated and diffuse reflectances, \( q^-_{c,R} \) and \( q^-_{d,R} \) are the collimated and diffuse reflection radiations, respectively.

### 3.2. Input parameters of the model

The interface reflection factors are the important input parameters of the model. The calculations of \( r_c \) and \( r_d \) have been discussed in detail in our previous work [4]. In this work, the calculations of \( r_{c,c} \) and \( r_{d,d} \) need to be illustrated. The refractive index and extinction coefficient of the coating were denoted as \( n_c \) and \( \kappa_c \), and those of the stainless-steel substrate were denoted as \( n_s \) and \( \kappa_s \), respectively. For the coating, \( \kappa_c \ll n_c \), therefore it can be regarded as a perfect dielectric. Whereas, the stainless-steel substrate should be regarded as an absorbing medium because \( \kappa_s \) cannot be ignored. When light propagates to the surface of the absorbing medium through the perfect dielectric, the interface reflection factor of the parallel polarized light, \( r_{||} \), and that of the vertical polarized light, \( r_{\perp} \), can be calculated according to Fresnel’s law [27]:

\[
r_{||} = \frac{(p - n \sin \theta_i \tan \theta_i)^2 + \bar{q}^2}{(p + n \sin \theta_i \tan \theta_i)^2 + \bar{q}^2}
\]

\[
r_{\perp} = \frac{(n \cos \theta_i - p)^2 + \bar{q}^2}{(n \cos \theta_i + p)^2 + \bar{q}^2}
\]
where \( \theta_i \) is the incident angle, and the expressions for \( p \) and \( q \) are as follows
\[
p^2 = \frac{1}{2} \left[ (n_i^2 - \kappa_i^2 - n^2 \sin^2 \theta_i)^2 + 4n_i^2 \kappa_i^2 \right]
+ (n_i^2 - \kappa_i^2 - n^2 \sin^2 \theta_i)]
\]
\[
q^2 = \frac{1}{2} \left[ (n_i^2 - \kappa_i^2 - n^2 \sin^2 \theta_i)^2 + 4n_i^2 \kappa_i^2 \right]
- (n_i^2 - \kappa_i^2 - n^2 \sin^2 \theta_i)]
\]
(13)
(14)
The incident light is nonpolarized in our work, thus the reflection factor corresponding to the incident angle \( \theta_i \) can be expressed
\[
r_{sc}(\theta_i) = \frac{1}{2} (r_s + r_l)
\]
(15)
In our work, \( \theta_i \) is approximately zero, and \( r_{sc} \) can be further simplified as
\[
r_{sc} = \frac{(n_i - n)^2 + \kappa_i^2}{(n_i + n)^2 + \kappa_i^2}
\]
(16)
The parameter of \( r_{sd} \) can be calculated by the following formula
\[
r_{sd} = \frac{\int_0^{2\pi} \int_0^\pi \int_0^\pi r_{sc}(\theta_i) \sin \theta_i \cos \theta_i d\theta_i}{\int_0^{2\pi} \int_0^\pi \int_0^\pi \sin \theta_i \cos \theta_i d\theta_i}
\]
(17)
where \( \phi \) is the azimuth angle.

As mentioned, the optical constants of the stainless-steel substrate and the coating are key input parameters for the calculation of the interface reflection factors. For the stainless-steel substrate, \( n_s \) and \( \kappa_s \) can be obtained by fitting the measured reflectance of the stainless-steel substrate via the Lorentz model [27, 28]:
\[
\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{i=1}^{N} \frac{\omega_p^2(\omega_m^2 - \omega^2)}{(\omega^2 - \omega_m^2)^2 + \omega_p^2\omega^2}
\]
(18)
\[
\varepsilon_i(\omega) = \sum_{i=1}^{N} \frac{\omega_p^2\omega_i^2}{(\omega_m^2 - \omega^2)^2 + \omega_p^2\omega^2}
\]
(19)
where \( \varepsilon_r \) and \( \varepsilon_i \) are the real and imaginary parts of the dielectric constant, respectively, \( \omega \) is the frequency, \( \varepsilon_\infty \) is a high-frequency constant, \( N \) is the order of the composite Lorentz model, \( \omega_p \) is the damping coefficient of the oscillator, \( \omega_m \) is the plasma frequency, \( \omega_i \) is the resonance frequency. The relationships between the dielectric constants and the optical constants are as follows [27, 28]
\[
\varepsilon_r = n_s^2 - \kappa_s^2
\]
(20)
\[
\varepsilon_i = 2n_s\kappa_s
\]
(21)
When light propagates to the opaque stainless-steel substrate through the air, the reflectance of the stainless-steel substrate is equal to the reflection factor at the interface between the air and stainless-steel substrate and can be expressed as
\[
R_s = \frac{(1 - n_i)^2 + \kappa_i^2}{(1 + n_i)^2 + \kappa_i^2}
\]
(22)
Based on the measured reflectance of the stainless-steel substrate and via equations (18) to (22), \( n_s \) and \( \kappa_s \) can be determined. Figure 5(a) and (b) show the measured and fitted reflectances of the stainless-steel substrate and the calculated \( n_s \) and \( \kappa_s \), respectively.

Besides, for the coating, \( n \) is not static but should be dynamically determined with the respect of camouflage coating volume compositions and can be determined by the following formula:
\[
n = \sum f_i n_i
\]
(23)
where \( f_i \) and \( n_i \) are the volume fraction and refractive index of component \( i \). The refractive index of the camouflage coating mainly depends on the dry coating resin matrix and water absorbed by the coating because the volume fraction of pigment is much smaller than those of the dry coating resin matrix and water. The refractive index of the dry coating resin matrix can be inverted via a ray-tracing method according to the transmittance and reflectance of the dry coating membrane without \( \text{Cr}_2\text{O}_3 \), i.e., dry PVA membrane [4], and that of water can be derived from the literature [29]. The data of the refractive indexes of the dry PVA membrane and water is shown in figure 6.
Figure 5. Measured and fitted reflectances (a) and the fitted optical constants (b) of the stainless-steel substrate.

Figure 6. Refractive indexes of the dry PVA membrane [4] and water [29].
In addition to the interface reflection factors, the absorption and scattering coefficients of the coating are also the important input parameters and can be determined by

\[ k_m f_m + f_c C_{abs} / V_c + k_w f_w = k_c \] \hspace{1cm} (24)
\[ s = f_c C_{sca} / V_c \] \hspace{1cm} (25)

where \( k_m \) and \( k_w \) are the absorption coefficients of the dry coating without Cr\(_2\)O\(_3\) and water, \( C_{abs} \) and \( C_{sca} \) and \( V_c \) are the absorption cross-section, scattering cross-section and volume of a single Cr\(_2\)O\(_3\) particle, and \( f_c \) is the volume fraction of the Cr\(_2\)O\(_3\) particles in the coating. \( k_m \) also can be obtained by the same inversion method as the refractive index of the PVA membrane [4], and \( k_w \) can be derived from the literature [29]. The data of \( k_m \) and \( k_w \) are shown in figure 7(a). \( C_{abs} / V_c \) and \( C_{sca} / V_c \) are constant due to the same kind of Cr\(_2\)O\(_3\) particles used in our work and defined as \( k_c \) and \( s_c \), respectively. \( k \) and \( s \) of the camouflage membrane containing a certain content of Cr\(_2\)O\(_3\) have been calculated in our previous work [4], and therefore \( k_c \) and \( s_c \) can be derived according to equations (24) and (25) and these data are shown in figure 7(b). It should be noted that both equations (24) and (25) are only applicable to particle independent scattering [30]. Our previous work has shown that the Cr\(_2\)O\(_3\) particles scatter independently in the camouflage membrane when \( f_c \) is lower than 2.4% [4].

4. Results and discussion

4.1. Model validation

To verify the reliability of the calculated reflectance of the camouflage coating via the four flux K-M model, the 0.13 mm thick camouflage coating containing 0.2% and 21% volume fractions of Cr\(_2\)O\(_3\) and water, respectively, was taken as a sample. A photo and an SEM image of the sample, and an SEM/EDX mapping of chromium element on the surface of the sample are shown in figures 8(a)–(c), respectively. From figures 8(a) and (b), it can
be seen that the camouflage coating resembles the color of the green leaf, and exhibits a dense structure. As shown in figure 8(c), the distribution of chromium element is roughly uniform, which confirms the assumption in section 3.1 that the Cr$_2$O$_3$ particles are uniformly distributed in the coating. The measured and calculated reflectances of the sample are shown in figure 9 and a good agreement between the calculated data and the experiment data can be found.

As mentioned in section 3.2, the changed volume fraction of Cr$_2$O$_3$ can affect the absorption and scattering coefficients of the camouflage coating, thereby affecting its spectral reflectance. In addition, the reflectance of the camouflage coating is also affected by the variation of the volume fraction of water. We will discuss the effects of the volume fractions of Cr$_2$O$_3$ and water on the reflectance of the camouflage coating in the following sections.

4.2. Effect of Cr$_2$O$_3$ content on the reflectance
The 0.2 mm thick dry camouflage coating and membrane without the stainless-steel substrate were taken as samples for calculation. The calculated reflectances of the above samples with $f_c$ equal to 0%, 0.2%, 0.4%, 0.8%, 1.6% and 2.4%, respectively, are shown in figure 10. It is found that the reflectance of the membrane without Cr$_2$O$_3$, i.e., PVA membrane, is maintained below 10% over the wavelength range of 300 nm to 2500 nm, and two very weak water absorption bands appear at 1460 nm and 1940 nm, respectively, as shown in figure 10(a). Whereas, the reflectance of the coating without Cr$_2$O$_3$, i.e., PVA coating, is higher than that of the PVA membrane, and obvious absorption bands appear at 1460 nm and 1940 nm, respectively, as shown in figure 10(b).

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Figure 8. A photo (a) and an SEM image (b) of the camouflage coating, an SEM/EDX mapping of chromium element on the surface of the camouflage coating (c).

Figure 9. Measured and calculated reflectances of the verification camouflage coating sample (thickness is 0.13 mm, and $f_c$ and $f_w$ are 0.2% and 21%, respectively).
The reflection spectrum of an *Osmanthus fragrans* leaf is also shown in figure 10, and it can be seen that the membrane and coating containing Cr₂O₃ are able to simulate all of the basic reflectance characteristics of the *Osmanthus fragrans* leaf. For the camouflage membrane, with the increase of $f_c$, the reflectance changes little in the visible light region, whereas, in the infrared region, the reflectance tends to increase, as shown in figure 10(a). For the camouflage coating with $f_c$ below 0.8%, the reflectance gradually decreases in the visible light region with increased $f_c$, while an irregular trend can be observed in the infrared region; when $f_c$ is above 0.8%, the same trend of the reflectance changing with $f_c$ as the camouflage membrane is observed in the range from 300 nm to 2500 nm, besides, the reflectance of the coating gradually approaches to that of the membrane with increased $f_c$. It can be concluded that the influence of the optical property of the stainless-steel substrate on the reflectance of the coating gradually decreases with increased $f_c$, until $f_c$ reaches 0.8%, the coating is capable of concealing the reflectance characteristics of the stainless-steel substrate and realizing camouflage. Figure 11 shows the correlation coefficient between the spectral reflectances of the camouflage coating and the *Osmanthus fragrans* leaf, and indicates that the correlation coefficient increases with increased $f_c$ for $f_c$ below 0.8%; whereas a gradually decreased trend of the correlation coefficient can be observed for $f_c$ above 0.8%, but still maintains above 0.86.

Based on the absorption and scattering coefficients of Cr₂O₃, the role of the Cr₂O₃ particles of the camouflage coating can be elucidated. As shown in figure 7(b), an absorption valley appears around 535 nm in the absorption coefficient curve of Cr₂O₃, leading to a peak appearing at the corresponding wavelength in the
reflectance curve of the camouflage coating, which helps the camouflage coating simulate the ‘green peak’ of the leaf. Due to the weak absorption and strong scattering in the range of 750 nm to 1300 nm, the reflectance of the camouflage coating maintains at a high value and shows the characteristics of ‘red edge’ and the ‘near-infrared plateau’ of the leaf. With the increased \( f_\text{c} \), both the absorption and scattering of the \( \text{Cr}_2\text{O}_3 \) particle cloud will increase. The increased absorption in the visible light region will cause more light to be absorbed by the camouflage coating, leading to an attenuation of the reflection radiation. Whereas, the increased scattering over the whole wavelength range will result in more light being backscattered to the incident plane during the propagation along the incident direction, leading to an enhancement of the reflection radiation.

To further analyze the influence mechanism of \( \text{Cr}_2\text{O}_3 \) content on the reflectance characteristics and the differences of the reflectances between the coating and membrane, the total reflectance, \( R_\text{d} \), collimated reflectance, \( R_\text{s} \), and diffuse reflectance, \( R_\text{d} \), of the above samples at 535 nm and 1000 nm representing the visible light and infrared regions, were calculated and shown in figures 12(a) to (d), respectively. At 535 nm and 1000 nm, for both the coating and membrane, when \( f_\text{c} \) increases from 0 to 0.8%, part of the collimated light is scattered and converted into diffuse light, thus \( R_\text{s} \) decreases significantly. When \( f_\text{c} \) is above 0.8%, the collimated reflectance is further attenuated with increased \( f_\text{c} \) and finally approaches to \( r_\text{c} \) shown in figure 12(e). It’s worth noting that when \( f_\text{c} \) is below 0.8%, \( R_\text{s} \) of the coating is higher than that of the membrane at 535 nm and 1000 nm. This is because the reflection factor for the collimated light at the interface between the stainless-steel substrate and the coating is significantly larger than that at the interface between air and the bottom surface of the membrane, i.e., \( r_\text{c}, r_\text{s} \), as shown in figures 12(e) and (f). In the term of \( R_\text{d} \), for both the coating and membrane containing \( f_\text{c} \) above 0.8%, the absorption and scattering coefficients increase simultaneously with increased \( f_\text{c} \) at 535 nm according to \( k_\text{c} \) and \( s_\text{c} \), as shown in figure 7(b), thus \( R_\text{d} \) is almost constant; whereas \( R_\text{d} \) is enhanced significantly with increased \( f_\text{c} \) at 1000 nm due to the enhanced scattering coefficient and the invariant absorption coefficient. It is important to realize that \( R_\text{d} \) of the coating is very close to that of the membrane both at 535 nm and 1000 nm, indicating that there is little effect of the optical property of the stainless-steel substrate on the coating diffuse reflectance. From figure 12 we can see that \( R_\text{d} \) is the main contributor of \( R \) for \( f_\text{c} \) above 0.8%, thereby, the trend changing with \( f_\text{c} \) of \( R \) follows that of \( R_\text{d} \).

### 4.3. Effect of water content on the reflectance

The 0.2 mm thick camouflage coating with \( f_\text{c} \) equal to 0.8% was taken as a sample for calculation. The reflectances of the above coating with \( f_\text{w} \) equal to 0%, 10%, 20%, 30%, 40% and 50% were calculated through the four flux K-M model and shown in figure 13. It is seen that the reflectance changes little in the visible light region, whereas gradually increases and decreases in the ranges of 800 nm to 1300 nm and water absorption bands, respectively.

The increase of \( f_\text{w} \) affects the reflectance of the camouflage coating in two aspects, i.e., the absorption coefficient increases in the region of water absorption bands due to the higher absorption coefficient of water compared with that of the PVA membrane; besides, the refractive index decreases over the whole wavelength region.
range due to the lower refractive index of water compared with that of the PVA membrane. The increased absorption in the region of water absorption bands causes more light to be absorbed by the camouflage coating and a significant attenuation of reflection radiation, whereas, the decreased refractive index of the camouflage coating results in changes in the interface reflection factors, which affects the reflection radiation in the whole wavelength range. Figure 14 shows the calculated interface reflection factors of the camouflage coatings containing different water contents. It can be seen that with the increase of \( f_w \), both \( r_c \) and \( r_d \) gradually decrease, while both \( r_{sc} \) and \( r_{sd} \) change little. To further analyze the influence mechanism of water content on the reflectance characteristics of the camouflage coating, \( R_c, R_{sc}, \) and \( R_{sd} \) of the above samples at 535 nm, 1000 nm and 1460 nm representing the visible light, near-infrared with unchanged absorption and scattering, and water absorption bands regions were calculated and shown in figures 15(a) to (c), respectively. In the term of \( R_c \), as mentioned in section 4.2, \( R_c \) of the coating is approximate to \( r_c \) for \( f_c \) above 0.8%, therefore, the variation trend

![Figure 12](image-url)
Figure 13. Calculated reflectances of the camouflage coatings with different \( f_c \) (thickness is 0.2 mm, and \( f_c \) is 0.8%).

Figure 14. Calculated interface reflection factors, \( r_c \) (a), \( r_d \) (b), \( r_{c,d} \) (c) and \( r_{c,d} \) (d), of the camouflage coatings containing different \( f_w \) (thickness is 0.2 mm, and \( f_c \) is 0.8%).
Figure 15. Calculated collimated reflectance, $R_c$, diffuse reflectance, $R_d$, and total reflectance, $R$, of the coatings with different $f_w$ at 535 nm (a), 1000 nm (b) and 1460 nm (c) (thickness is 0.2 mm, and $f_c$ is 0.8%).
with $f_w$ of $R_c$ follows that of $R_c$, i.e., $R_c$ of the above camouflage coatings decreases with the increased $f_w$ as shown in figures 15(a) to (c). In the term of $R_d$, in the case of unchanged absorption and scattering, the decreased $r_d$ causes $R_d$ to increase according to equation (10), consequently, $R_d$ of the above camouflage coatings increases with the increased $f_w$ as shown in figures 15(a) and (b); in the water absorption bands region, the significantly increased absorption coefficient with the increased $f_w$ leads to a significant attenuation of $R_d$ as shown in figure 15(c). In the term of $R_d$, at 535 nm, with the increased $f_w$, the changes of $R_c$ and $R_d$ cancel each other out, and thus $R$ remains almost unchanged, as shown in figure 15(a); at 1000 nm and 1460 nm, the trend changing with $f_c$ of $R$ follows that of $R_d$ because the variation of $R_d$ is dominant, as shown in figures 15(b) and (c).

Moreover, it is noteworthy that compared with the reflection spectrum of the *Osmanthus fragrans* leaf which is also shown in figure 13, two reflection valleys appear at 2100 nm and 2310 nm in the reflection spectrum of the camouflage coating, respectively, corresponding to the absorption peaks of the PVA membrane according to $k_m$ shown in figure 7(a). These reflection valleys may cause the camouflage targets easy to be recognized by hyperspectral imaging detection, whereas, they can be weakened and even masked by the strong absorption of a large amount of water. Figure 16 shows the correlation coefficient between the spectral reflectances of the camouflage coating and the *Osmantus fragrans* leaf, and indicates that the correlation coefficient increases with increased $f_w$, and reaches 0.954 for $f_w$ equal to 50%. Our previous research has shown that the water content of the camouflage membrane was controlled by LiCl content [21]. In the same environment, the higher the LiCl content, the more moisture the camouflage membrane adsorbs from the ambient air. In conclusion, by changing the amount of LiCl content in the camouflage coating, the hydrophilicity of the camouflage coating can be adjusted, therefore, the reflectance characteristics of the camouflage coating over the wavelength range from 1300 nm to 2500 nm can be regulated to improve the camouflage performance under the background of vegetation.

5. Conclusions

A camouflage coating composed of hydrophilic material and green pigment particles of Cr$_2$O$_3$ was coated on the stainless-steel substrate. In the range from 1300 nm to 2500 nm, the reflectance of the pure PVA coating is similar to that of the leaves, and four basic reflectance characteristics of the leaves can be simulated by adding Cr$_2$O$_3$. With the increased volume fraction of Cr$_2$O$_3$, the influence of the optical property of the stainless-steel substrate on the reflectance of the coating gradually decreases, until the volume fraction of Cr$_2$O$_3$ reaches 0.8%, the coating can basically mask the reflectance characteristics of the stainless-steel substrate and realize camouflage. In addition, the reflectance of the camouflage coating can be further improved by absorbing moisture from a high humidity environment. The absorbed water exerts two effects on the camouflage coating: the refractive index decreases leading to the increased reflectance of the camouflage coating in the range from 800 nm to 1300 nm; the absorption coefficient significantly increases around 1460 nm and 1940 nm, which...
helps the reflectance of the camouflage coating decrease in the corresponding region and approaching to that of the leaves. The reflectance of the stainless-steel substrate can be concealed by increasing the Cr$_2$O$_3$ content and the characteristic of water absorption bands can become more obviously by increasing the LiCl content.

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**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

**Disclosures**

The authors declare no conflicts of interest.

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