crystals

MDPI

Article

Investigation of Factors Affecting the Color of Serpentine Jade from Shandong, China

Shidie Deng and Ying Guo *

School of Gemmology, China University of Geosciences (Beijing), Beijing 100083, China
* Correspondence: guoying@cugb.edu.cn

Abstract: The color of serpentine jade is affected not only by the chemical composition, but also by some external factors. In this research, we quantitatively analyzed the color of serpentine jade and the influence of light sources, backgrounds, and thickness on its color. Thirty-six gem-quality serpentine jade samples from Tai'an, Shandong, China, were studied using eighteen Munsell neutral gray backgrounds, and three light sources (D65, F2, and A). It was found that the D65 light source appeared to be the most suitable for the display and sale of serpentine jade and the Munsell N9 background can make the color grading of serpentine jade more effective.

Keywords: serpentine jade; color; thickness; light source; background

check for updates

Citation: Deng, S.; Guo, Y. Investigation of Factors Affecting the Color of Serpentine Jade from Shandong, China. *Crystals* **2023**, *13*, 431. https://doi.org/10.3390/cryst13030431

Academic Editor: Francesco Capitelli

Received: 7 February 2023
Revised: 20 February 2023
Accepted: 22 February 2023
Published: 2 March 2023

1. Introduction

Serpentine jade is a high-quality mineral aggregate with serpentine minerals as its primary constituents. Serpentine jade has a typical yellow-green and dark green appearance, a waxy luster, and a delicate cryptocrystalline structure. Due to its beautiful appearance and properties, serpentine jade is very suitable for carving various ornamental stones and handicrafts, and is therefore very popular in the market and sought after by many jewelry lovers. Serpentine jade has a long history of mining and use [1]. In ancient times, serpentine jade was widely used in the Mediterranean region, Asia, Oceania, and the Americas as a material for jewelry making, decoration, and carving [2]. Carved knives and chisels made of serpentine jade, dating from 6800 to 7200 years ago, were unearthed at the "Xinyue" Cultural Site in Shenyang, Liaoning Province, China. Serpentine jade is generally abundant in nature and is mainly distributed in China [3], South Korea [4,5], New Zealand [6], the USA [7,8], Mexico [9,10], and Italy [11]. Among them, China is a very important and the largest trade market. Serpentine jade is one of the four famous jades in China and has many admirers. In China, there are many important provinces for the production of serpentine jade, such as those of Liaoning [12,13], Gansu [14], and Shandong [15–17].

Serpentine jade can be divided into two classes, depending on the origin and geological characteristics of the deposit: serpentine jade of ultrabasic rocks and rocks rich in magnesium carbonate [3]. The first type is formed by serpentinization of the rocks, which occurs due to hydrothermal alteration of ultrabasic rocks such as magnesium-rich peridotite, augite peridotite, and pyroxenitic rocks to replace minerals such as olivine, tremolite, and pyroxene in the rocks. The second type is mainly formed by the regional metamorphism of the Proterozoic magnesium-rich carbonate rocks (dolomite, magnesite, etc.), which is produced in a certain stratigraphic horizon and controlled by it. It is a stratified deposit. The samples selected in this paper are serpentine jade produced in Tai'an, Shandong Province, China. It belongs to ultrabasic rock jade ore [17,18]. Since this jade comes from Mountain Tai, it is called "Taishan Jade".

Previous studies of serpentine jade have focused on basic gemological, spectral and geochemical properties, and simple comparative studies between different habitats. Hou Xu et al. studied the geological and geochemical properties of Taishan jade and discussed its origin. The results suggest that the Taishan jade was formed though the metamorphism of small amphiboles in the Archean Taishan Group. There are four ore bodies in the mining area, which are roughly divided by the intruded rock bodies (veins) such as diabase dike, plagioclasite dike, monzogranite dike, lamprophyre dike and quartz dike in the later period [17]. Cheng Youfa et al. studied the gemological and spectral properties of Taishan jade [15]. It is mainly yellow-green and dark green, opaque to translucent, with waxy to glass luster, a refractive index between 1.56 and 1.57 and an SG between 2.60 and 2.65. The whole of Taishan jade is dense and blocky, characterized under the microscope by a blade blastic texture and lepidoblastic texture, and equigranular blastic texture according to the grain size. The main rock-forming mineral is antigorite.

Regarding the origin of the color of the serpentine jade, Xue Lei et al. believe that the yellow tone of serpentine jade is mainly related to the electronic transition of the d-d crystal field of Fe^{3+} [19]. Yin Ke et al. believe that serpentine jade's color is related to the Fe^{3+}/Fe^{2+} ratio [20], and yellow-green serpentine jade has a higher Fe^{3+}/Fe^{2+} ratio than dark green serpentine jade. Wang Yongya et al. believe that serpentine jade's green tone is determined by Fe^{2+}, while the yellow is determined by the joint action of Fe^{3+} and Fe^{2+} [21]. According to Zhang Shiting [22], as the iron content increases, the blue tone of blue-green serpentine jade increases and the green tone decreases. Previous authors therefore believed that iron is the main element that determines the color of serpentine jade, but they have not performed a quantitative analysis of the color, nor have they investigated other factors affecting the color of this material.

In addition to the chemical composition, also external factors like light sources and backgrounds that can influence the color of a gem [23–25]. For instance, under different light sources, the color-changing garnet can turn from red to green. In accordance with the requirements of the evaluation of the quality of the jewelry and the uniformity of the light source and the <<GB/T 20146-2006>> national standard, we selected three light sources D65 (6500 K), F2 (4150 K), and A (2856 K) to study the effect of different light sources on serpentine jade's color appearance. The Munsell N0.5 to N9 color cards were chosen as backgrounds to study the effect of different backgrounds on serpentine jade's color.

In recent years, colorimetry has been widely used in gemological research. Many scholars have studied the color genesis of jadeite [26–28], diamond [29], sapphire [30], amethyst [31], garnet [32,33], peridot [34], and iolite [23] using colorimetric methods. However, there are few studies on the factors affecting the color of serpentine jade. In this paper, we quantitatively analyzed the serpentine jade's color and analyzed the effect of light sources, backgrounds, and thickness on the serpentine jade's color.

2. Materials and Methods

2.1. Materials

We selected 36 serpentine jade samples from Tai'an City, Shandong Province, most of which are square with a side length of 3.00 cm. All samples have the same thickness except those used for thickness experiments. Table 1 shows the gemological characteristics of the serpentine jade samples and Figure 1 shows some of the samples.

Table 1. The gemological characteristics of the serpentine jade samples.

Characteristics	Results
Color	Blue-green to yellow-green
Luster	Vitreous luster
RI	1.55–1.57
Diaphaneity	Opaque to translucent
SG	2.592–2.667
Fluorescence reaction	Non-fluorescence

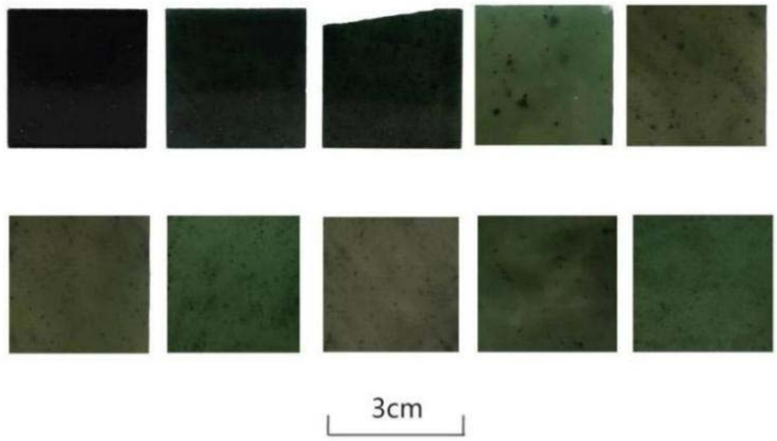


Figure 1. Some of the serpentine jade samples (D65).

2.2. Methods

2.2.1. Color Measurement

We used the X-Rite SP62 hand-held spectrophotometer to determine the color parameters of 36 serpentine jade samples. All test points were selected at a clean and uniform position in the sample's center with a 6 mm diameter, under the D65 light source. The test condition was transmission mode, viewing angle of 2°, measuring range of 400–700 nm, specular reflection excluded. The final color data are the average of the three tests.

2.2.2. CIE1976 L*a*b* Uniform Color Space

The CIE 1976 L*a*b* uniform color space is widely applied for the color quantitative characterization and measurement, and is recommended by the International Commission on Lighting. It is a three-dimensional system consisting of vertical axes L* and plane axes a* and b*. The axe L* stands for the lightness of a color, and the range of values is (0, 100), indicating pure black to white. Color coordinate a* represents the degree of red to green, and the value range is (−128, 217). Positive values are red and negative values are green. The color coordinate b* indicates the degree of yellow to blue, and the value range is (−128, 127). Positive values are yellow and negative values are blue. The chroma C* can be calculated using the a* and b* according to Formula (1), and C* represents the shade of the color, while the hue angle h° represents the angle rotated counterclockwise from the +a* axis and is used to represent the color type, and can be calculated using the a* and b* according to Formula (2) [35–37].

$$C* = \sqrt{a^{*2} + b^{*2}} \tag{1}$$

$$h^\circ = \arctan\frac{a^*}{b^*} \tag{2}$$

The formula we used to compute the color difference of the serpentine jade samples at different thicknesses is CIE DE2000 (ΔE_{00}), which provides better visual uniformity than the CIELAB (ΔE^*_{ab}) formula.

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)^2\left(\frac{\Delta H'}{K_H S_H}\right)^2} \tag{3}$$

Among them, $\Delta L'$ is the lightness difference, $\Delta C'$ is the chroma difference, and $\Delta H'$ is the hue angle difference. The function R_T is to reduce the mutual effect in the blue region between the hue angle and chroma. K_L, K_C, and K_H are two useful combinations, namely CIE DE2000 (2:1:1) and CIE DE2000 (1:1:1) [38,39], to calibrate the parameters for the environment. S_L, S_C, and S_H are the calibration functions for the visual uniformity absence in the CIELAB formulation. To better evaluate chromatic aberration, we selected the CIE DE2000 (1:1:1) parameter set since it can provide better perceptual performance.

2.2.3. Light Sources Change

To investigate the effect of light sources on the serpentine jade samples' color, the color parameters of 36 serpentine jade samples were measured under three types light sources (D65, F2, and A) with the Munsell N9 background, using an X-Rite SP62 hand-held spectrophotometer, based on the CIE 1976 L*a*b* uniform color space.

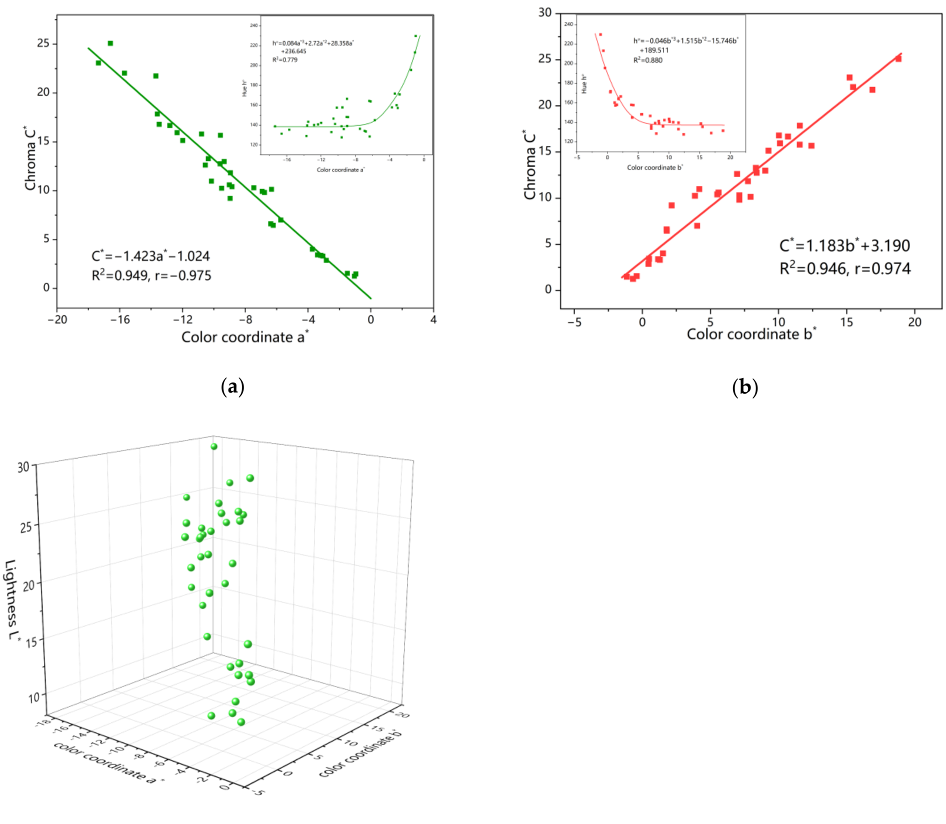
2.2.4. Backgrounds Change

To investigate the effect of backgrounds on the serpentine jade samples' color appearance, based on the CIE 1976 L*a*b* uniform color space, we tested the color parameters of 36 serpentine jade samples under single light source with eighteen Munsell neutral gray backgrounds, using an X-Rite SP62 hand-held spectrophotometer.

3. Results and discussion

3.1. Color Quantification

Color parameters of the 36 serpentine jade samples under the D65 light source and with Munsell N9 background are as follows: L*∈(9.97, 29.59), a*∈(−17.36, −0.96), b*∈(−1.14, 18.81), chroma C*∈(1.26, 25.09), hue angle h°∈(127.70, 229.90). The color appearance of serpentine jade samples are consistent with these data. Figure 2c shows the three-dimensional projection plot of the 36 samples' color parameters.



(**a**) (**b**)

(**c**)

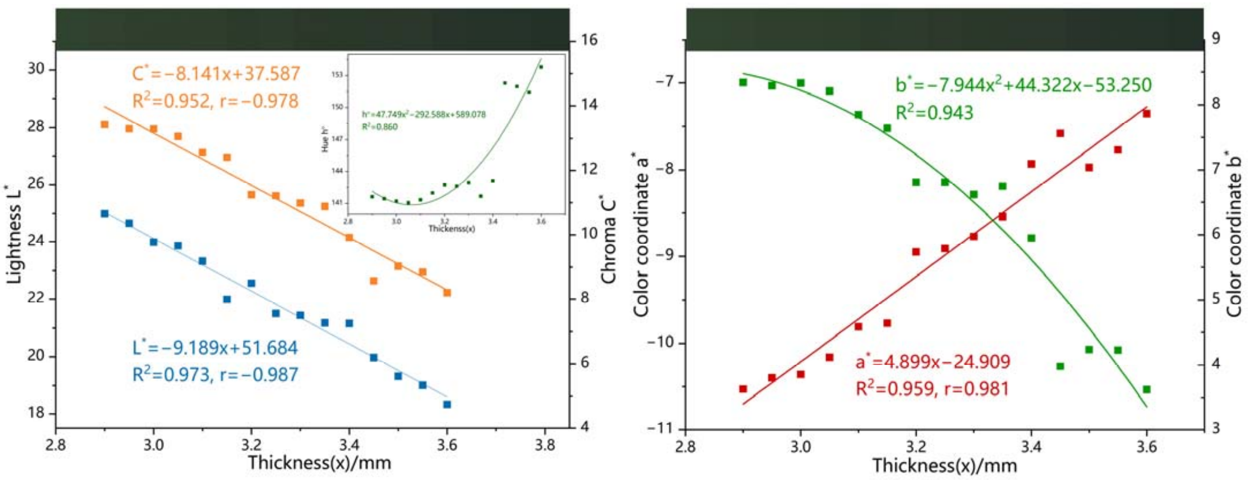
Figure 2. (**a**) The relation between the a* and the chroma C*, hue angle h°; (**b**) the relation between the b* and the chroma C*, hue angle h°; (**c**) color parameters of 36 serpentine jade samples plotted in the CIE 1976 L*a*b*uniform color space.

The color coordinates a*, b* and the chroma C* show clear linear correlations (R^2 = 0.949, 0.946) according to the analysis of 36 serpentine jade samples' color parameters. The chroma C* decreases as the color coordinate a* increase and increases as the b* increase. Moreover, there is little difference between the R^2 or r of the a* and b*; therefore, chroma C* is jointly controlled by the a* and b*. R^2 stands for the goodness of fit. It is the degree of fit between the regression line and the observed value. The observed value fits the regression line better when the R^2 value is closer to 1. The r is called the Pearson correlation coefficient. It is used to judge how well two variables are correlated. The linear correlation between two variables is stronger when the absolute value of r is closer to 1. The correlation between the chroma C* and the a*, b* is greater than that between the hue angle h° and the a*, b*. Therefore, the influence of the a* and b* on the chroma C* is greater than that of hue angle h°. The +b* axis is located in the yellow region, while the −a* axis is located in the green region in the CIE 1976 L*a*b* uniform color space, suggesting that chroma C* of serpentine jade is mainly affected by the green hue and yellow hue. Moreover, it is observed that the degree of fitting between the hue angle h° and color coordinate b* (R^2 = 0.880) is greater than that between the hue angle h° and a* (R^2 = 0.779). Therefore, the influence of b* on the hue angle h° of serpentine jade is greater than that of the a*.

3.2. Influence of the Thickness on the Color of Serpentine Jade

The color parameters of the serpentine jade samples at each thickness were measured under the D65 light source and with the Munsell N9 background using an X-Rite SP62 hand-held spectrophotometer.

Correlations of color parameters of serpentine jade samples with different thicknesses revealed that thickness has a clear influence on the color of it. The brightness L* and chroma C* show a very significant negative linear correlation with thickness, that is, the brightness L* and chroma C* of serpentine jade increase as the thickness decreases, while the color becomes brighter and thicker. The hue angle h° decreases with decreasing thickness, that is, as the thickness decreases, the hue of blue-green serpentine jade shifts towards the green, while that with green hue shifts towards yellow-green (Figure 3a). In the process thinning, the light absorption of serpentine jade gradually decreases, while the transmitted and reflected light increases, and this leads to an increase in lightness. The yellow tone is the one with the highest brightness; thus, the hue of the serpentine will gradually move closer to the yellow tone.



(**a**) (**b**)

Figure 3. (**a**) Relationship between the thickness with the lightness L*, chroma C* and hue angle h°; (**b**) relationship between the thickness with color coordinates a* and b*.

The correlation between thickness and lightness L* (R^2 = 0.973, r = −0.987) was greater than that between thickness and chroma C* (R^2 = 0.952, r = −0.978) and hue angle h° (R^2 = 0.860). Therefore, thickness has the greatest influence on lightness L*, the second highest on chroma C*, and the least influence on hue angle h°.

Furthermore, we observe that the color coordinate a* decreases while the b* increases with the decrease in thickness, which determines an increase in chroma C* according to Formula 1. The correlation between thickness and color coordinate a* is greater than that between thickness and color coordinate b*. Therefore, the influence of thickness on color coordinate a* is greater than that on b*.

At the same time, using Formula 3 to calculate the corresponding color change value ΔE_{00} during the thickness change of the sample, the variation in thickness (Δx) and color difference (ΔE_{00}) are analyzed as follows:

$$\Delta E_{00} = 8.847\Delta x + 0.434\ (R^2 = 0.973,\ r = 0.986).$$

When the $\Delta E_{00} > 3$, the human eye can recognize the color difference of a gem. When ΔE_{00} is 3, the thickness change Δx is 0.29 mm. In other words, when the thickness of serpentine jade changes by about 0.29 mm, the human eye can recognize a significant color change of serpentine jade.

3.3. Influence of the Different Light Sources on the Color Appearance

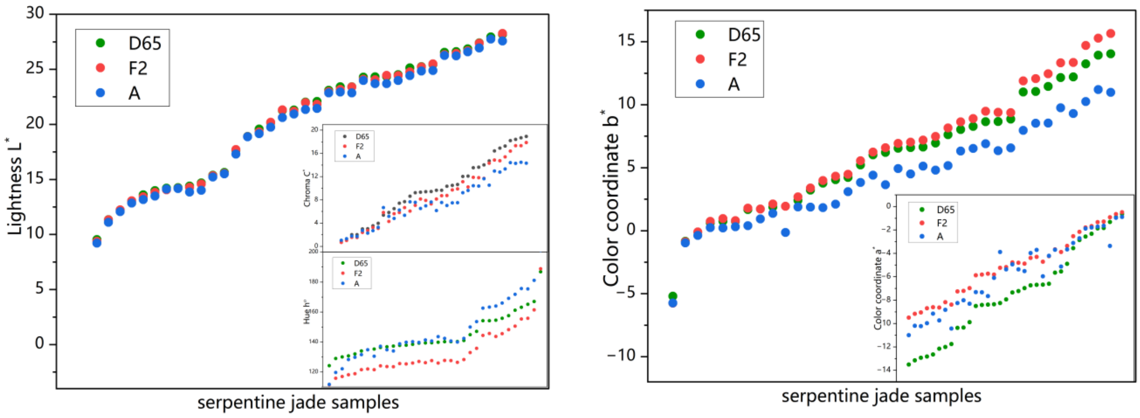
We used the X-Rite SP62 hand-held spectrophotometer to test the color parameters of 36 serpentine jade samples under three types light sources (D65, F2, and A) with the Munsell N9 background. We conducted a one-way analysis of variance to analyze these color parameters and Table 2 shows the results. Here, *p* is the significance coefficient and is used to judge the significance of the effect. When p <0.05, the effect is significant.

Table 2. The ANOVA results of the color parameters of samples.

Color Parameters	df	Mean Square	F	*p*
L*	2	1.526	0.051	0.951
a*	2	49.746	4.672	0.011
b*	2	18.443	0.691	0.504
C*	2	42.906	1.774	0.175
h°	2	1889.927	6.868	0.002

The results reported in Table 2 show that different light sources have no obvious influence on lightness L* (p = 0.951) and b* (p = 0.504) of the sample, and have little influence on chroma C* (p = 0.175), but have a significant influence on the a* (p = 0.011) and hue angle h° (p = 0.002). F denotes the variance between groups. The F of the hue angle h° (F = 6.868) is larger than color coordinate a* (F = 4.672), indicating that different light sources affect the hue angle h° most.

The comparison of color parameters under D65 (6500 K), F2 (4150 K), and A (2856 K) light sources is shown in Figure 4. The color temperatures and spectral energy distributions of different light sources are different, which affect their rendering index, determine their color rendering properties, and, lastly, will produce different colors when illuminated on a gem [23]. The lightness of the sample is related to the light source's color temperature. The source can radiate higher brightness when the color temperature of the source is higher. The more light the sample can receive and reflect under this light source, the more the lightness L* increases and the visual effect therefore becomes brighter. However, due to the low transparency of serpentine jade, the light reflected and transmitted by the sample is still limited and the increase is not obvious even under the irradiation of the higher color temperature light source. Therefore, the lightness L* of serpentine jade does not change significantly when the light source switches from D65 to F2 and A.



(**a**) (**b**)

Figure 4. (**a**) The lightness L*, chroma C*, and hue angle h° under three light sources; (**b**) the color coordinates a* and b* under three light sources.

The energy of the fluorescence sources (F2 and A) is mainly in the red and yellow regions, while the solar source D65 is mostly in the blue-green region. Since the hue of the sample is between yellow-green and blue-green, the D65 source helps the sample to produce a green color, while the F2 source makes the hue closer to green and yellow-green. Therefore, the hue angle h° of the sample decreases when the light source changes from D65 to F2. The A light source will make the yellow-green sample closer to yellow and the blue-green sample closer to blue. Therefore, the hue angle h° of the yellow-green sample with low hue angle value will decrease, while the hue angle h° of the blue-green sample with high hue angle value will increase when the light switches from D65 to A.

The color coordinate a* of the sample is negative while the b* is positive. When light source switches from D65 to A and F2, the color coordinate a* increases successively and the green density decreases. Additionally, under the D65 light source, a* is the smallest. Under F2 and D65 light sources with higher yellow density, color coordinate b* is larger, while under A light source with the lowest yellow density, color coordinate b* is the smallest. However, when the light source switches from F2 to D65, the decrease in b* is less than that of a*, that is, the decrease in the absolute value of b* is less than the increase in the absolute value of a*. Therefore, according to Formula 1, the chroma C* will increase; therefore, the samples have largest chroma C* values under the D65 light source. This is because the light of F2 and A sources tends to be an orange-red color light. Thus, if orange-red light superimposes on the serpentine jade sample with a green tone, the green color will weaken and the chroma C* will decrease.

In summary, the D65 light source is the most suitable one for the display and sale of serpentine jade, as it can help serpentine jade to exhibit higher lightness and chroma, and is more suitable for serpentine jade to show green color.

3.4. Influence of the Backgrounds on the Color Appearance

Even a neutral background with varying shades of grey can generate a marked difference in the color appearance of serpentine jade, due to its luster and transparency [25]. Therefore, for this study we only used the D65 light source.

The color parameters of 36 serpentine jade samples were measured using the X-Rite SP62 hand-held spectrophotometer with 18 Munsell neutral backgrounds (N0.5–N9) under the D65 light source. Figure 5 shows the color change process of the sample. In addition, color parameters of all samples for the 18 backgrounds are plotted in a box plot (Figure 6). Table 3 shows the color parameters' average data of the serpentine jade samples on 18 Munsell neutral backgrounds.

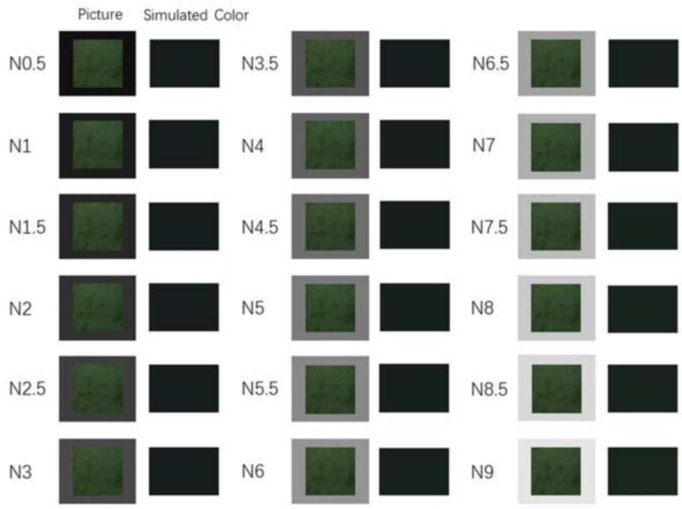


Figure 5. Pictures of a serpentine jade sample on 18 Munsell neutral backgrounds, shown with the associated colors.

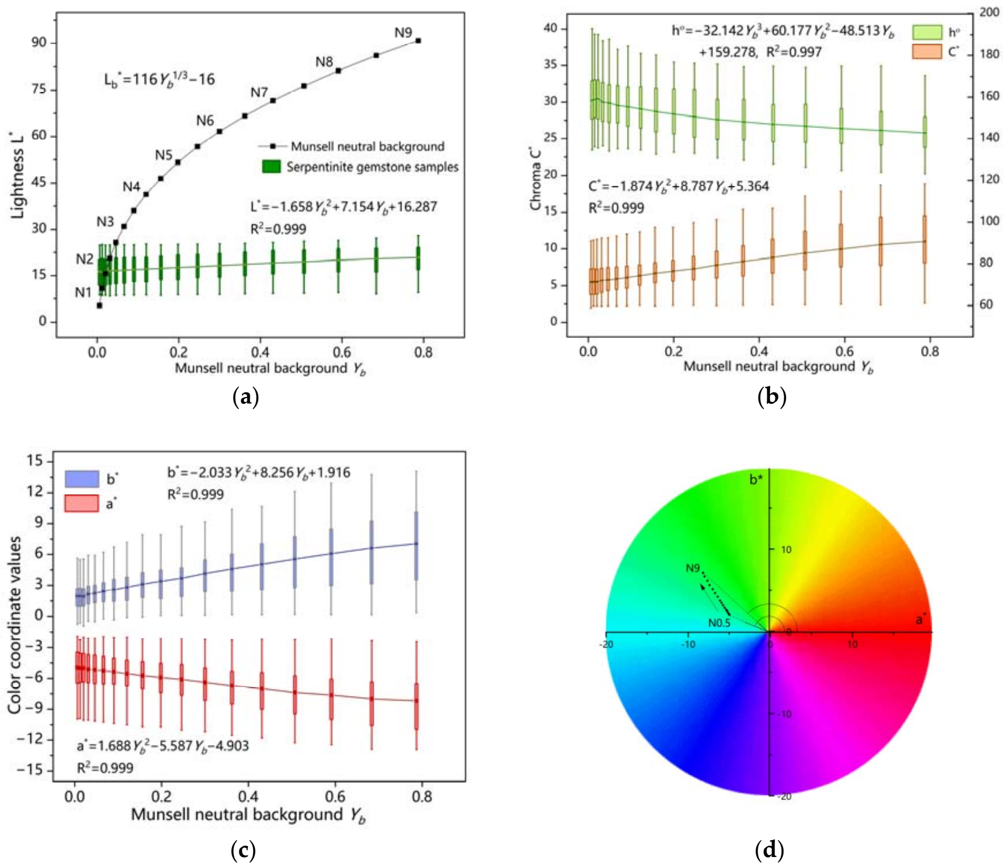


Figure 6. Changes in the color of serpentine jade samples produced by changes in the Munsell neutral background under D65 light source. (**a**) a box diagram of the lightness L* of the samples (and lightness of the background) and the luminance factor; (**b**) a box diagram of the chroma C* (and hue angle h°) and the luminance factor; (**c**) a box diagram of the color coordinates a*, b* and the luminance factor. (**d**) the plane-projection plot of the a* and b* mean values for each of the 36 serpentine jade samples with each background; the hue angle of the samples gradually decreases as the lightness of the background increases.

Table 3. Serpentine jade's color on 18 Munsell neutral backgrounds.

Backgrounds		**N0.5**	**N1**	**N1.5**	**N2**	**N2.5**	**N3**	**N3.5**	**N4**	**N4.5**
Luminance factor Y_b		0.006	0.012	0.020	0.031	0.046	0.066	0.090	0.120	0.156
Lightness L_b*		5.08	10.56	15.49	20.44	25.56	30.88	35.98	41.22	46.45
Color parameters'	L*	16.37	16.26	16.43	16.52	16.62	16.78	16.96	17.15	17.37
average of the	a*	−4.95	−5.00	−5.00	−5.12	−5.16	−5.26	−5.37	−5.55	−5.73
samples	b*	2.03	2.02	2.00	2.22	2.29	2.47	2.63	2.87	3.16
		N5	**N5.5**	**N6**	**N6.5**	**N7**	**N7.5**	**N8**	**N8.5**	**N9**
Luminance factor Y_b		0.198	0.246	0.300	0.362	0.431	0.507	0.591	0.684	0.787
Lightness L_b*		51.61	56.68	61.65	66.67	71.62	76.50	81.35	86.21	91.10
Color parameters'	L*	17.65	17.91	18.24	18.63	19.07	19.46	19.99	20.46	20.84
average of the	a*	−5.92	−6.10	−6.39	−6.71	−7.00	−7.38	−7.64	−7.99	−8.18
samples	b*	3.45	3.74	4.20	4.64	5.11	5.61	6.12	6.66	7.09

The Munsell neutral background has 37 lightness levels ranging from 0 to 100 and is represented by N0.5 to N9.5 at intervals of N = 0.25. Each lightness level has a daytime luminance factor (Y_b) corresponding to it. The relationship between the Y_b and lightness L_b* of the Munsell neutral background is as follows:

$$L_b^* = 116{Y_b}^{1/3} - 16$$

There are two ways to mix colors: additive and subtractive. The first way is to obtain colors by mixing lights with different spectral power distributions through the projection of colored beams. As the intensity increases, so does the lightness of the mixed colors. The second way is to obtain colors by superimposing color layers that act as spectral filters [40]. Thus, combining the gem with the background is subtractive color mixing.

Figure 6a shows that the lightness of the samples increases as the background lightness increases. By fitting the Munsell neutral background luminance factor with the sample's lightness, the relationship between the lightness L* of samples and Y_b can be obtained as follows:

$$L^* = -1.658{Y_b}^2 + 7.154Y_b + 16.287\ (R^2 = 0.999).$$

The variation in the lightness of the serpentine jade samples with different grayscale backgrounds is due to the sample itself having some transparency. The higher the background lightness, the more light is reflected from or passes through the sample. Therefore, the increase in the lightness of the background leads to an increase in the lightness of the serpentine jade sample.

Figure 6b shows the variation of the chroma C* and hue angle h° of the serpentine jade sample as a function of background. As the lightness of the background increases, the chroma C* increases while the hue angle h° decreases. By fitting the chroma C* and hue angle h° to the Munsell neutral background luminance factor Y_b, we obtain the following relation:

$$C^* = -1.874{Y_b}^2 + 8.787Y_b + 5.364\ (R^2 = 0.999).$$

$$h^\circ = -32.142{Y_b}^3 + 60.177{Y_b}^2 - 48.513Y_b + 159.278\ (R^2 = 0.997).$$

Unlike the relation between the lightness of serpentine jade and the lightness of background, the effect of the different grey neutral backgrounds on the chroma of serpentine jade does not follow a subtractive mixing law, since the neutral background has no chroma. According to Figure 2, there is a clear linear correlation between the chroma C* and color coordinates a*, b*. The +b* axis is located in the yellow region, while the −a* axis in the green one in the CIE 1976 L*a*b*uniform color space, indicating that the chroma of serpentine jade is mainly controlled by green and yellow hues. Since yellow hue has the highest lightness, as the lightness of the background increases, the color coordinate b* value of the sample also increases (Figure 6c), while the value of coordinate a* also decreases and the absolute value increases, which ultimately leads to the increase in the chroma C* of the sample. At the same time, we found that the increase in color coordinate b* was greater than the decrease in coordinate a*; thus, the color casting point gradually approached the +b* axis, and the hue angle h° decreased (Figure 6d).

According to these results, with the increase in the Munsell neutral background lightness, the lightness L* and chroma C* of serpentine jade increase, while the hue angle h° decreases. Moreover, the serpentine jade samples have greater color differentiation in the Munsell N9 color card, which makes it easier to distinguish the colors of samples in this background. Therefore, the Munsell N9 color card is more suitable for the color classification of serpentine jade, since this background can improve the classification accuracy.

4. Conclusions

Our investigation have show that the thickness of serpentine jade has a noticeable effect on its color. During the thickness reduction process, the chroma C* and lightness L* of serpentine jade increase, while the hue angle h° decreases. Thickness has the greatest effect on the lightness L*, followed by chroma C*, and the least effect on the serpentine jade's hue angle h°. When the thickness of serpentine jade changes by about 0.29 mm, a significant change in the color can be recognized by the human eye. This result may provide a theoretical basis for the working of serpentine jade.

Different light sources have little influence on the lightness L* and chroma C* of serpentine jade but significant on the hue angle h°. The D65 light source has the highest color temperature and can radiate the most light, making the lightness L* of serpentine jade the highest. Moreover, serpentine jade has the highest chroma C* and can better show green tones under the D65 light source. Thus, the D65 light source is the most suitable for the display and sale of serpentine jade.

The color of serpentine jade is affected by the Munsell neutral background of different shades of grey. As the background lightness increases (N0.5–N9), the lightness of serpentine jade also increases. However, the increase in lightness is not relevant due to the low transparency of serpentine jade. When the lightness of the background increases, the absolute value of the color coordinate b* of serpentine jade increases, while a* decreases, resulting in the increase in the chroma C*. Furthermore, since the increase in b* is greater than the decrease in a*, the hue angle h° approaches the +b* axis, and its value decreases. The color differentiation of serpentine jade is more pronounced and the colors are more easily distinguished on the Munsell N9 background. Therefore, Munsell N9 background appears to be the most suitable for making accurate color grading of serpentine jade.

Author Contributions: Conceptualization, S.D. and Y.G.; methodology, S.D. and Y.G.; software, S.D.; validation, S.D. and Y.G.; formal analysis, S.D.; investigation, S.D. and Y.G.; resources, S.D. and Y.G.; data curation, S.D.; writing—original draft preparation, S.D.; writing—review and editing, Y.G.; visualization, S.D.; supervision, Y.G.; project administration, Y.G.; funding acquisition, Y.G. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the School of Gemmology, China University of Geosciences (Beijing) and Professor Ying Guo.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Lab of Gemmology, School of Gemmology, China University of Geosciences, Beijing, for support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, B.S.; Wu, X.T.; Sun, Y.F.; Ritchey, M.; Fan, A.C.; Zhang, Y.Y.; Yu, G.; Song, Y.B. Complex raw materials and the supply system: Mineralogical and geochemical study of the jade artefacts of the Longshan Culture (2400–2000$_{\mathrm{BCE}}$) from Sujiacun site in coastal Shandong, China. *Archaeometry* **2020**, *63*, 1–18. [CrossRef]
2. Guillot, S.; Hattori, K. Serpentinites: Essential Roles in Geodynamics, Arc Volcanism, Sustainable Development, and the Origin of Life. *Elements* **2013**, *9*, 95–98. [CrossRef]
3. Huang, X.Z. Serpentine jade deposit in China. Miner. *Guide Non-Met. Miner. Ind. China* **2005**, *3*, 55–57.
4. Kim, S.W.; Santosh, M.; Park, N.; Kwon, S. Forearc serpentinite mélange from the Hongseong suture, South Korea. *Gondwana Res.* **2011**, *20*, 852–864. [CrossRef]
5. Kim, W.S. Serpentine Jade (Bowenite) in Korea. *J. Earth Sci.* **2000**, *11*, 103–106.
6. Scott, J.M. An updated catalogue of New Zealand's mantle peridotite and serpentinite. *New Zealand J. Geol. Geophys.* **2020**, *63*, 428–449. [CrossRef]
7. Sonzogni, Y.; Treiman, A.H.; Schwenzer, S.P. Serpentinite with and without brucite: A reaction pathway analysis of a natural serpentinite in the Josephine ophiolite, California. *J. Miner. Pet. Sci.* **2017**, *112*, 59–76. [CrossRef]
8. Gates, A.E. Domainal failure of serpentinite in shear zones, State-Line mafic complex, pennsylvania, u.s.a. *J. Struct. Geol.* **1992**, *14*, 19–28. [CrossRef]
9. Gonzalez, G.; Ortega, F. Electron microprobe study of the Tehuitzingo chromite-bearing serpentinite, Southern Mexico. *Electron. Microsc.* **1998**, *1*, 373–374.
10. Robert, B. Collecting Banded Serpentine in New Mexico. *Rock Gem.* **2004**, *34*, 88–91, 98.
11. Adamao, I.; Diella, V.; Bocchio, R.; Rinaudo, C.; Marinoni, N. Gem-Quality Serpentine from Val Malenco, Central Alps, Italy. *Gems Gemol.* **2016**, *52*, 38–49. [CrossRef]
12. Zhang, L.J. A study on the composition and properties of Xiuyan jade in Liaoning Province. *Acta Mineral. Sin.* **2002**, *2*, 137–142.
13. Li, D.Z.; Yu, S.X.; Wang, Z. Discussion on the jade-forming regularity of Xiuyan jade in Xiuyan area, Liaoning province. *Contrib. Geol. Miner. Resour. Res.* **2013**, *2*, 249–255.
14. Ge, Y.L.; Wang, S.Q.; Guo, J.; Wu, T.; Fan, G.Z.; Liu, Y.; He, L.W. Geochemical and gemological characteristics of Yuanyang jade from Wushan County, Gansu Province. *Mineral. Petrol.* **2011**, *30*, 151–161.
15. Cheng, Y.F.; Li, J.J.; Fan, C.L.; Zhang, Z.G. Gemological characteristics of "Taishan jade". *J. Gems Gemol.* **2011**, *1*, 29–32.
16. Cheng, Y.F.; Li, J.J.; Zhu, P.M.; Fan, C.L.; Shan, G.Q. Origin characteristics and nomenclature of Taishan jade. *J. Synth. Cryst.* **2014**, *43*, 2324–2328.
17. Hou, X.; Wu, R.H.; Wang, S.Q.; Shi, W. Mineralogical and petrological characteristics of Taishan Jade. *Mineral. Petrol.* **2011**, *30*, 169–174.
18. Qiu, W.; Zhai, B.; Wei, B.; Zhang, J.Z.; Zhang, D.Y. Genetic characteristics and development and utilization value of ultrabasic rock serpentine jade—Take the Taishan jade deposit as an example. *Miner. Explor.* **2021**, *12*, 1792–1797.
19. Xue, L.; Wang, Y.Q.; Fan, J.L. Spectroscopic characteristics of yellow serpentine jade. *Laser Infrared* **2009**, *3*, 267–270.
20. Yin, K.; Pan, Y.; Yu, S.J.; Li, T.; Han, W. Mineralogical and gemological characteristics of "Kunlun Gold Jade" in Xinjiang. *J. Gems Gemmol.* **2016**, *18*, 15–19.
21. Wang, Y.Y.; Gan, F.X. Coloration mechanism and chromaticity of Xiuyan Jade of China. *Spectrosc. Spectr. Anal.* **2012**, *32*, 2305–2310.
22. Zhang, S.T. Study on Gemstone Mineralogical and Gemological Characteristics of Blue-Green Serpentine Jade. Master's Thesis, China University of Geosciences, Beijing, China, 2020.
23. Liu, X.; Guo, Y. Study on the Color-Influencing Factors of Blue Iolite. *Minerals* **2022**, *12*, 1356. [CrossRef]
24. Tang, J.; Guo, Y.; Xu, C. Metameric effects on peridot by changing background color. *J. Opt. Soc. Am. A* **2019**, *36*, 2030–2039. [CrossRef] [PubMed]
25. Jiang, Y.S.; Guo, Y.; Zhou, Y.F.; Li, X.; Liu, S.M. The effects of munsell neutral grey backgrounds on the colour of chrysoprase and the application of AP clustering to chrysoprase colour grading. *Minerals* **2021**, *11*, 1092. [CrossRef]
26. Guo, Y.; Wang, H.; Li, X.; Dong, S.R. Metamerism Appreciation of Jadeite-Jade Green under the Standard Light Sources D 65, A and CWF. *Acta Geol. Sin.* **2016**, *90*, 2097–2103. [CrossRef]
27. Guo, Y.; Zong, X.; Qi, M. Feasibility study on quality evaluation of Jadeite-jade color green based on GemDialogue color chip. *Multimed. Tools. Appl.* **2019**, *78*, 841–856. [CrossRef]
28. Pan, X.; Guo, Y.; Liu, Z.Y. Impact of different standard lighting sources on red jadeite and color quality grading. *Earth Sci. Res.* **2019**, *23*, 371–378. [CrossRef]
29. Liu, F.K.; Guo, Y.; Lv, S.J.; Chen, G.G. Application of the entropy method and color difference formula to the evaluation of round brilliant cut diamond scintillation. *Mathematics* **2020**, *8*, 1489. [CrossRef]
30. Han, J.Y.; Guo, Y.; Liu, S.T. Environmental issues on color quality evaluation of blue sapphire based on gemdialogueTM color comparison charts. *Ekoloji Dergisi.* **2018**, *27*, 1365–1376.
31. Cheng, R.; Guo, Y. Study on the effect of heat treatment on amethyst color and the cause of coloration. *Sci. Rep.* **2020**, *10*, 14927. [CrossRef]
32. Sun, Z.; Palke, A.C.; Renfro, N. Vanadium- and Chromium-Bearing Pink Pyrope Garnet: Characterization and Quantitative Colorimetric Analysis. *Gems Gemol.* **2016**, *51*, 348–369. [CrossRef]
33. Qiu, Y.; Guo, Y. Explaining Colour Change in Pyrope-Spessartine Garnets. *Minerals* **2021**, *11*, 865. [CrossRef]
34. Tang, J.; Guo, Y.; Xu, C. Color effect of light sources on peridot based on CIE1976 $L^*a^*b^*$ color system and *round* RGB diagram system. *Color Res. Appl.* **2019**, *44*, 932–940. [CrossRef]

35. Kirillova, N.P.; Vodyanitskii, Y.N.; Sileva, T.M. Conversion of soil color parameters from the Munsell system to the CIE-L*a*b* system. *Eurasian Soil Sci.* **2015**, *48*, 468–475. [CrossRef]
36. Vodyanitskii, Y.N.; Kirillova, N.P. Application of the CIE-L*a*b* system to characterize soil color. *Eurasian Soil Sci.* **2016**, *49*, 1259–1268. [CrossRef]
37. Mahajan, M.P.; Bandyopadhyay, S. Characterization and optimization of color attributes chroma (C^*) and lightness (L^*) in offset lithography halftone print on packaging boards. *Color Res. Appl.* **2019**, *45*, 325–335. [CrossRef]
38. Mangine, H.; Jakes, K.; Noel, C. A preliminary comparison of CIE color differences to textile color acceptability using average observers. *Color Res. Appl.* **2005**, *30*, 288–294. [CrossRef]
39. Perez, M.D.M.; Ghinea, R.; Herrera, L.J.; Ionescu, A.M.; Pomares, H.; Pulgar, R.; Paravina, R.D. Dental ceramics: A CIEDE2000 acceptability thresholds for lightness, chroma and hue differences. *J. Dent.* **2011**, *39*, e37–e44. [CrossRef]
40. Simonot, L.; Hébert, M. Between additive and subtractive color mixings: Intermediate mixing models. *J. Opt. Soc. Am. A* **2013**, *31*, 58–66. [CrossRef]