Evaluations and analyses on the performance of liquid foundations from a materials science perspective

Jingru He [1], Xuedan Qian [1], Panpan Yang [1], Xujing Zheng [1] and Hu Huang [1,*]

[1] International Academy of Science, Proya Cosmetics Co., Ltd., Hangzhou, China
* Hu Huang, 588 Xixi Road, Hangzhou, Zhejiang, China, Tel: +86 191 1724 7161, e-mail: huanghu@proya.com

Abstract
A series of evaluation methods were developed for base makeup products from the perspective of materials science. The wettability of the liquid foundation to water, artificial sweat and artificial sebum were measured by the contact angle meter. The texture smoothing effect was examined by observing the roughness of the pore bio skin plate applied with the liquid foundation using the three-dimensional interference microscope. The distribution and time-dependent microstructural changes of cosmetic film on human facial skin surface were observed by the silicone replicator and scanning electron microscope. Additional properties of the liquid foundation, such as moisture permeability and makeup efficacy were also quantitatively evaluated using in vitro methods. Results revealed that the studied liquid foundations exhibited satisfactory waterproof, sweat-resistanct, sebum-resistant and moisture permeable properties, and could effectively reduce skin roughness and attenuate skin defects. Microscopic observations of the foundation film indicated that the product could evenly disperse on the skin surface and conceal imperfections. However, phenomena such as powders aggregating and mottling may occur over time due to sebum secretion and facial muscle movements. In conclusion, an evaluation system with simple implementation and high efficiency was successfully established for the liquid foundation in this study, offering powerful tools to accelerate the screening and debugging process in developing base makeup formulations.

Keywords: liquid foundations, performance characterization, materials science

1. Introduction

The liquid foundation is a versatile base makeup product that has become an essential part of many beauty routines. It can even out skin tone and disguise blemishes, fine lines and other imperfections [1-3]. With increasing demands of consumers regarding the efficacy of cosmetics, the need for functional evaluations of base makeup products such as long-lasting effect, concealing ability and moisturizing effect is also growing [4-6]. However, there is a lack of unified standards and clear measurement criteria for the functional evaluation of base makeup products. Currently, the mainstream method relies on a combination of clinical instrument testing and subjective consumer evaluations [7,8]. This approach presents challenges such as strong subjectivity, poor repeatability, long durations and high cost, along with the significant individual differences in the reliability and stability of scoring data [9]. Therefore, the functional evaluation of base makeup products is an important research field within the cosmetics industry.

To address the above issues, many studies have recently provided scientific methods and tools for evaluating foundation products. Nagaoka et al. used the standard deviation of reflectance as an indicator to assess the lasting effect of liquid foundations on 10 healthy volunteers using a hyperspectral imager. They found that the standard deviation at a wavelength of 800 nm can quantitatively evaluate the durability of liquid foundations without relying on the subject's oxygen saturation level [10]. Lee et al. used the standard deviation of image intensity values to evaluate the spreadability and covering power of liquid foundations applied to the face of 20 volunteers, and assessed the adhesion effect by measuring the total pixel area in photos of tape stripped from the arm. They discovered that the group using an "oscillating applicator" showed significantly better product spreadability, covering power and adhesion compared to the manual application group [11]. Kim et al. utilized a special photographic tool (photo gauge) equipped with color reference cards (ColorChecker Passport Video) to investigate changes in facial skin color among 516 Chinese female volunteers after applying liquid foundations, finding that the facial color of Chinese women became brighter and less rosy after makeup process [12]. This method offers a new approach for remote skin color research. In addition, Bui et al. employed an optical tensiometer to explore the spreading characteristics of artificial sebum on the liquid foundation deposited on biological skin plates, discovering that these characteristics depend on surface free energy and surface roughness, which are influenced by the solid content or thickness of the deposited film after solvent evaporation [13]. These mentioned diverse methods help accurately evaluate the performance of liquid foundations from multiple perspectives and address specific consumer demands, making them significant for improving product quality and promoting industry innovation.

To further broaden the research methods on the functions of base makeup products, the present study explored the performance of three commercially available long-lasting liquid foundations from the perspective of materials science. The waterproof, sweat resistance and sebum resistance of the liquid foundation were studied using contact angle measurements. The efficacy of the liquid foundation in improving skin roughness was examined by the three-dimensional interference microscope. The distribution of the foundation film on the skin surface and the structural changes over time were investigated at a microscopic level using the silicone replicator and scanning electron microscopy observation. Furthermore, the moisture permeability of the liquid foundation was evaluated quantitatively using the vapor transmittance tester, and the makeup efficacy of the liquid foundation was evaluated in vitro using the hazemeter, glossmeter and spectrophotometer. A comprehensive evaluation system that is objective and quantitative for liquid foundations is expected to establish utilizing various instruments, hoping to make a contribution for the development of base makeup products.

2. Materials and Methods

2.1 Materials

Three liquid foundations, named LF1, LF2 and LF3 are all commercially available. The normal, pore and freckle bio skin plates (Beaulax, Japan) are made of polyurethane elastomer and resemble human skin. The silicone replicator (SILFLO, Japan) is harmless to the human body and can replicate the cosmetic film against the skin. Artificial sweat and artificial sebum were purchased from the relevant manufacturers.

2.2 Contact angle measurements

2 mg/cm^2 of the sample was evenly applied to the normal bio skin plate using a finger with a fingerstall. After drying at room temperature for 30 minutes, the cosmetic film was formed. The contact angles (CAs) of deionized water, artificial sweat and artificial sebum were measured using the sessile drop method (OCA15EC, Germany) with/without the sample on the normal bio skin plate. All tests were performed in triplicate at random locations.

2.3 Skin surface microtopography

Sufficient amount of the sample was evenly applied to the pore bio skin plate using a finger with a fingerstall, and was dried at room temperature. The roughness (Sa) value of the blank pore bio skin plate and the plate applied with the sample were obtained from the three-dimensional interference microscope (NT9100, USA). All tests were performed in triplicate at random locations. The roughness reduction rate was calculated by [Sa (sample) – Sa (blank)] * 100%/ Sa (blank).

2.4 Microstructure of liquid foundation film

Two volunteers aged between 25 and 30 participated in the study. Before the test, the volunteers signed a written informed consent that contained basic information about the test. In detail, the volunteers were asked to clean the face with gentle cleanser and acclimate in a room with controlled temperature (21 ± 1)℃ and relative humidity (50 ± 10)% for 20 minutes. They were allowed to apply a certain amount of lotion on the face, and then evenly applied the sample using a powder puff on the half face. Skin replicas were collected at three time points on the nose wing and the nasolabial fold areas: before product use (T0), immediately after product use (T1), and 6 hours after product use (T6).

The silicone replicator was applied to the cosmetic film at different time points, and after hardening, the silicone replicator could be peeled off and the cosmetic film was copied down. The skin replicas were stored in a room with the temperature of (25 ± 2)℃ and humidity of (50 ± 5)%. The microstructure of liquid foundation film was observed using the cold field emission scanning electron microscope (SEM, SU8010, Japan).

2.5 Moisture permeability measurements

Sufficient amount of the sample was evenly applied to the soft leather using a finger with a fingerstall, and was dried at room temperature. The moisture permeability of blank soft leather and soft leather applied with the sample was measured by the vapor transmittance tester (W3/032, China). The testing temperature was set at 38℃ and the testing humidity was 80%.

2.6 Haze, gloss and color measurements

The haze of the sample with a thickness of 10 μm controlled by quartz plates and glass microbeads was measured using the hazemeter (CS-700, China). 2 mg/cm^2 of the sample was evenly applied to the normal and freckle bio skin plates using a finger with a fingerstall, and was dried at room temperature. The gloss and color values of the blank normal and freckle bio skin plates and the plates applied with the sample were measured using the glossmeter (DG60 Pro, China) and spectrophotometer (DS-700A, China), respectively.

2.7 Statistical analysis

The results were statistically analyzed using SPSS 25.0 software (IBM, USA). A paired - sample t-test was used to compare the changes before and after using the product. A p value < 0.05 was considered statistically significant for the analyses.

3. Results and Discussion

3.1 Contact angle measurements

The wetting behavior of the liquid foundation depends on factors such as the surface orientation in contact with different liquids, surface roughness and surface molecular mobility [13]. CAs between 90° and 180° indicates hydrophobic surface, while CAs between 0° and 90° indicates hydrophilic surface. Figure 1 showed the static water CAs of the sample deposited on the normal bio skin plate at room temperature. The water CA of the blank normal bio skin plate measured was (121.5±0.5)°, which may be related to the chemical properties and surface roughness of the polyurethane elastomer. Both LF1 and LF2 exhibited good water resistance, with water CAs achieving (100.1±1.2)° and (111.9±1.2)°, respectively. This behavior was attributed to the surface orientation of the silicone contained in the product at the solid/air interface. However, the water CA of LF3 measured was (88.3±1.0)°, indicating that it had a certain degree of hydrophilicity. The different wettability of the liquid foundation formulations may result from film-forming agents, silicone elastomers, surfactants, fillers and treated pigments, which formed micro-domains with varying roughness on the bio skin plate surface, thereby altering the interaction with water at the solid/liquid interface and ultimately leading to differences in the measured static CAs.

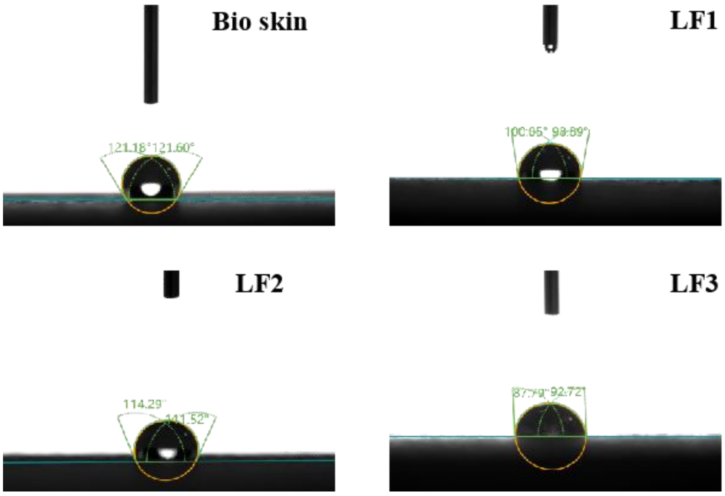


Figure 1. The deionized water CA images of the blank normal bio skin plate and the plate applied with the liquid foundation.

Sweat is typically weakly acidic, with a pH value between 4.5 and 5.5. This acidity arises from substances such as lactic acid and uric acid, which help inhibit the growth of bacteria on the skin surface, thereby protecting the skin from infection [14]. The artificial sweat used in this study is composed of lactic acid, sodium chloride and other ingredients. Figure 2 showed the static sweat CAs of the sample deposited on the normal bio skin plate at room temperature, and the sweat CA of the blank normal bio skin plate achieved (122.9±0.6)°. The measured sweat CAs of LF1, LF2 and LF3 were (108.5±2.5)°, (112.2±0.9)° and (103.8±1.1)°. All samples demonstrated good resistance to sweat, indicating they were suitable for use in hot weather, during exercise or any activity that may induce sweating, helping reduce the likelihood of makeup removal. Notably, the sweat CA of LF3 increased by about 15° compared to the water CA, likely due to the interaction between the salts and other dissolved substances in sweat with the foundation, resulting in changed surface property.

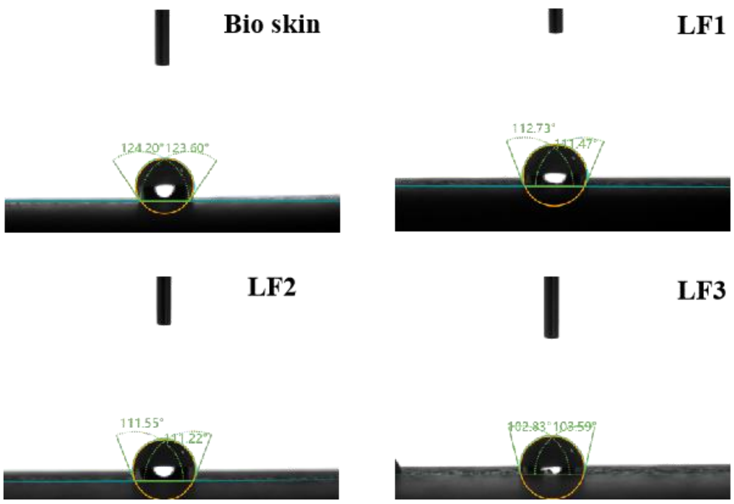


Figure 2. The artificial sweat CA images of the blank normal bio skin plate and the plate applied with the liquid foundation.

Human sebum has high lipophilicity and low surface tension, which may affect the spreading of cosmetic formulations and the adhesion of long-wear foundations on the skin [15]. It has been reported that the liquid foundation with a sebum equilibrium contact angle on the foundation film greater than 20° can be considered sebum-resistant [13]. Figure 3 showed the static sebum CAs of the sample deposited on the normal bio skin plate at room temperature, and the sebum CA of the blank normal bio skin plate achieved (31.4±2.1)°, which resembled the surface of actual human skin. The liquid foundation studied exhibited certain sebum-resistant property with the sebum CAs of (30.7±0.6)°, (21.1±0.9)° and (29.9±0.5)°. Sebum-resistance can not only prevent makeup removal due to sebum secretion, but also reduce the risk of pore blockage caused by the mixing of liquid foundations with lipid substances.

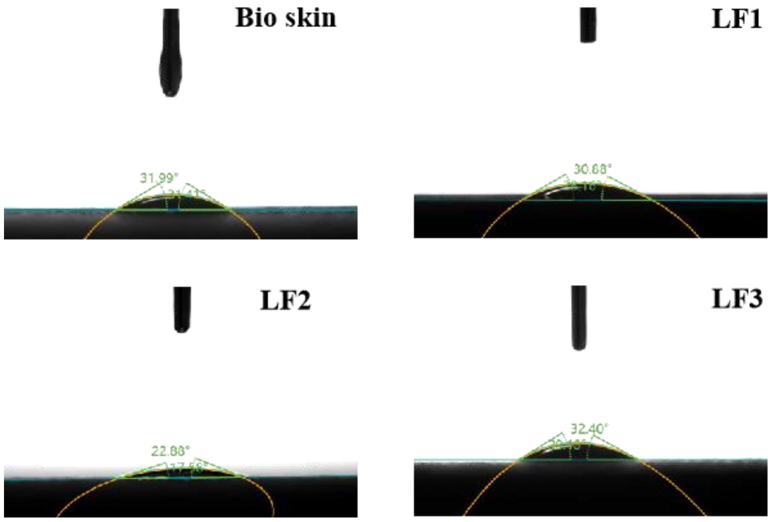


Figure 3. The artificial sebum CA images of the blank normal bio skin plate and the plate applied with the liquid foundation.

Figure 4 summarized the CA measuring results of three liquid foundations, providing a fast and straightforward way to evaluate the waterproof, sweat-resistant and sebum-resistant properties of liquid foundation products. During new products developing process, this approach can help predict the behavior of formulations in actual use, helping developers understand the impact of different ingredients on surface properties.

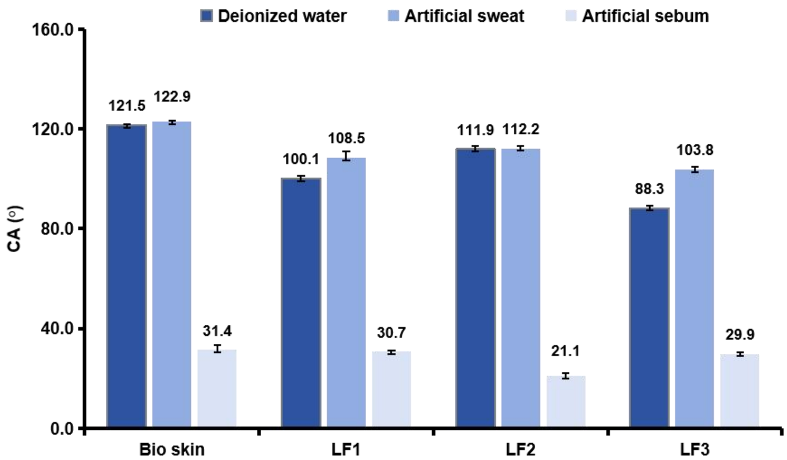


Figure 4. The CA histograms of the blank normal bio skin plate and the plate applied with the liquid foundation about deionized water, artificial sweat and artificial sebum, respectively.

3.2 Skin surface microtopography

Large skin roughness affects the optical path of light upon reaching the skin, resulting in decreased gloss and making the skin appear dull and lack the natural radiance of healthy skin [16]. Increased skin roughness is often accompanied by enlarged pores, making them more noticeable, especially in areas such as the facial T-zone where sebum secretion is more severe [17,18]. Figure 6 showed surface images of the pore bio skin plate and the statistical histograms of results. The surface of the blank pore bio skin plate exhibited clear grooves and unevenness, with a high Sa value of about 17 μm. After applied with the sample, the Sa values decreased to (10.2±0.3) μm, (8.7±1.1) μm and (9.2±0.9) μm for LF1, LF2 and LF3, achieving the decreasing rates of 41.7%, 50.3% and 45.3%. The result suggested that the liquid foundation can improve the appearance of imperfections by concealing them and make the skin look smoother. Furthermore, the varying degrees of improvement in surface roughness among three liquid foundations may be attributed to differences in film thickness and uniformity of the film after solvent evaporation.

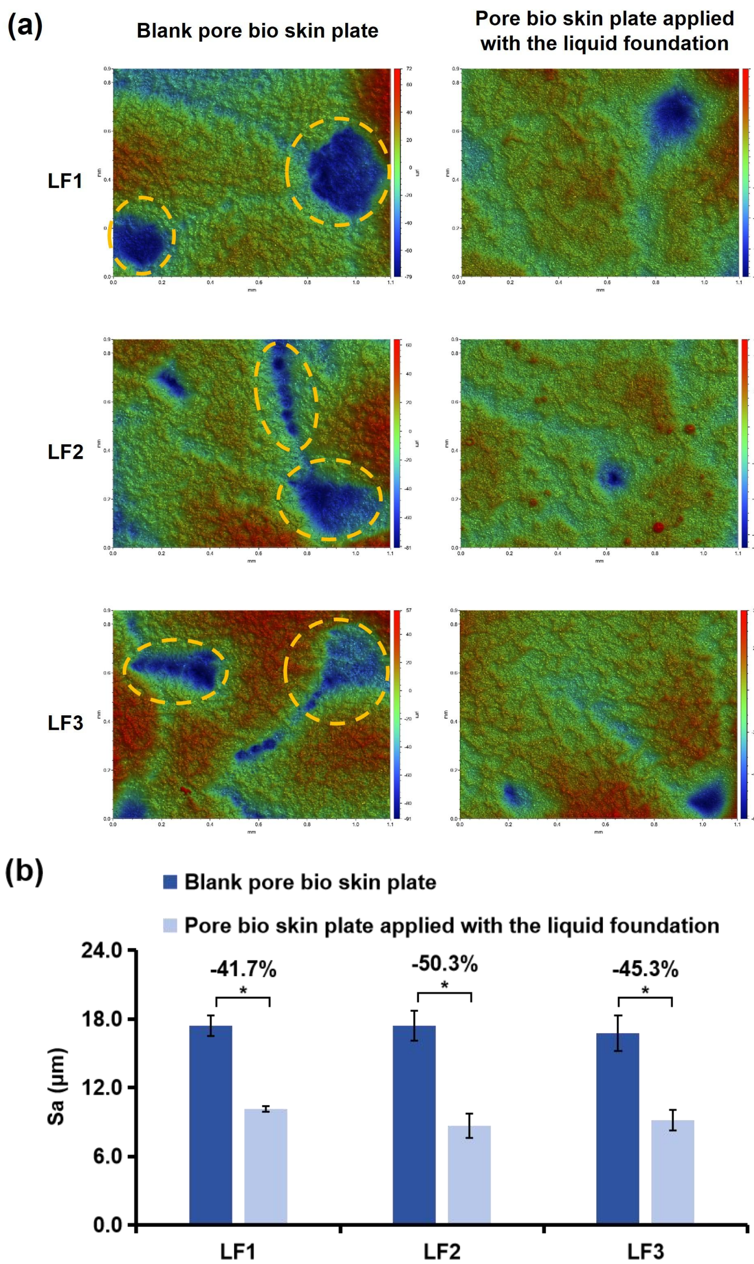
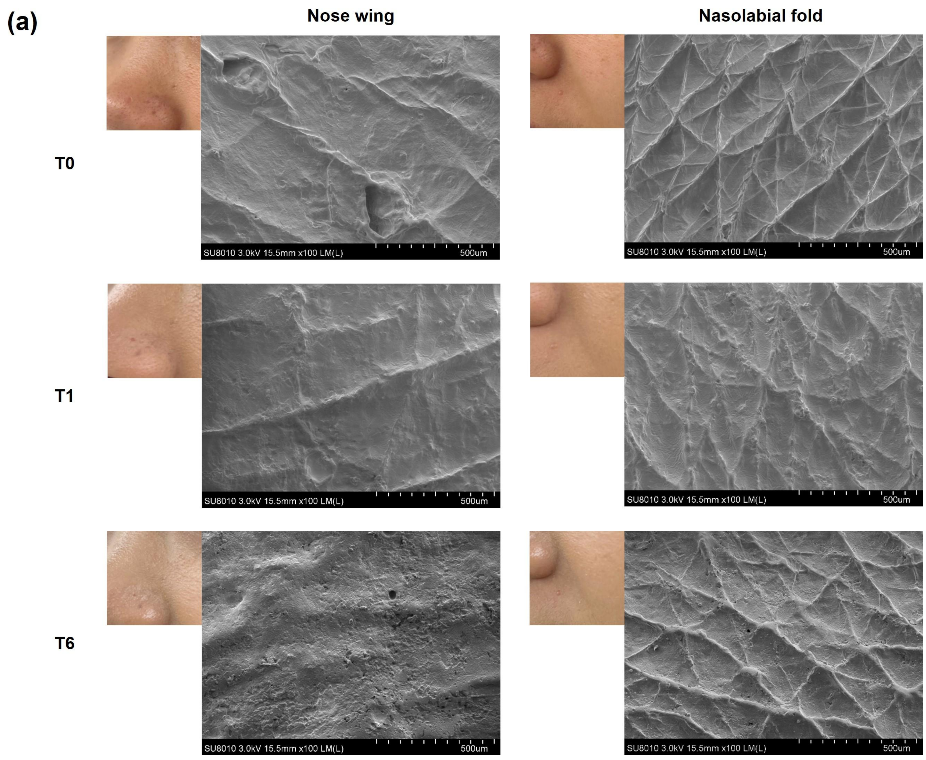


Figure 6. Surface images (a) and the statistical histograms (b) of the pore bio skin plate before and after the liquid foundation application.

3.3 Microstructure of liquid foundation film

Figure 7 showed the changes in application states of the liquid foundation over time. The collected skin replicas exhibited opposite concave and convex conditions relative to the skin, with the protruding parts in the image corresponding to the skin grooves. Before the application of the sample (T0), the skin texture was clearly uneven, accurately reflecting the grooves and bumps of the skin. Typically, the nose wing area showed more pores and the nasolabial fold area showed more wrinkles. After using the liquid foundation (T1), the skin surface appeared flatter, with less visible pores on the nose wing and lighter wrinkles in the nasolabial fold. The cosmetic film formed was uniform without obvious powder accumulation. This phenomena indicated concealing and smoothing functions of the liquid foundation, and the digital pictures also showed some brightening effects of the sample. Furthermore, these three liquid foundations all have better ability of covering pores than that of smoothing out wrinkles according to SEM images, indicating by invisible pores but still pronounced protruding lines at T1. After application for 6 hours (T6), the skin surface appeared oily and shining from the digital pictures. And SEM images showed mottled and uneven appearance of the cosmetic film with little bumps. The lines in the nasolabial fold turned more apparent even than the skin surface without the liquid foundation, which implied that ingredients in the product might aggregate and aggravate facial blemishes.



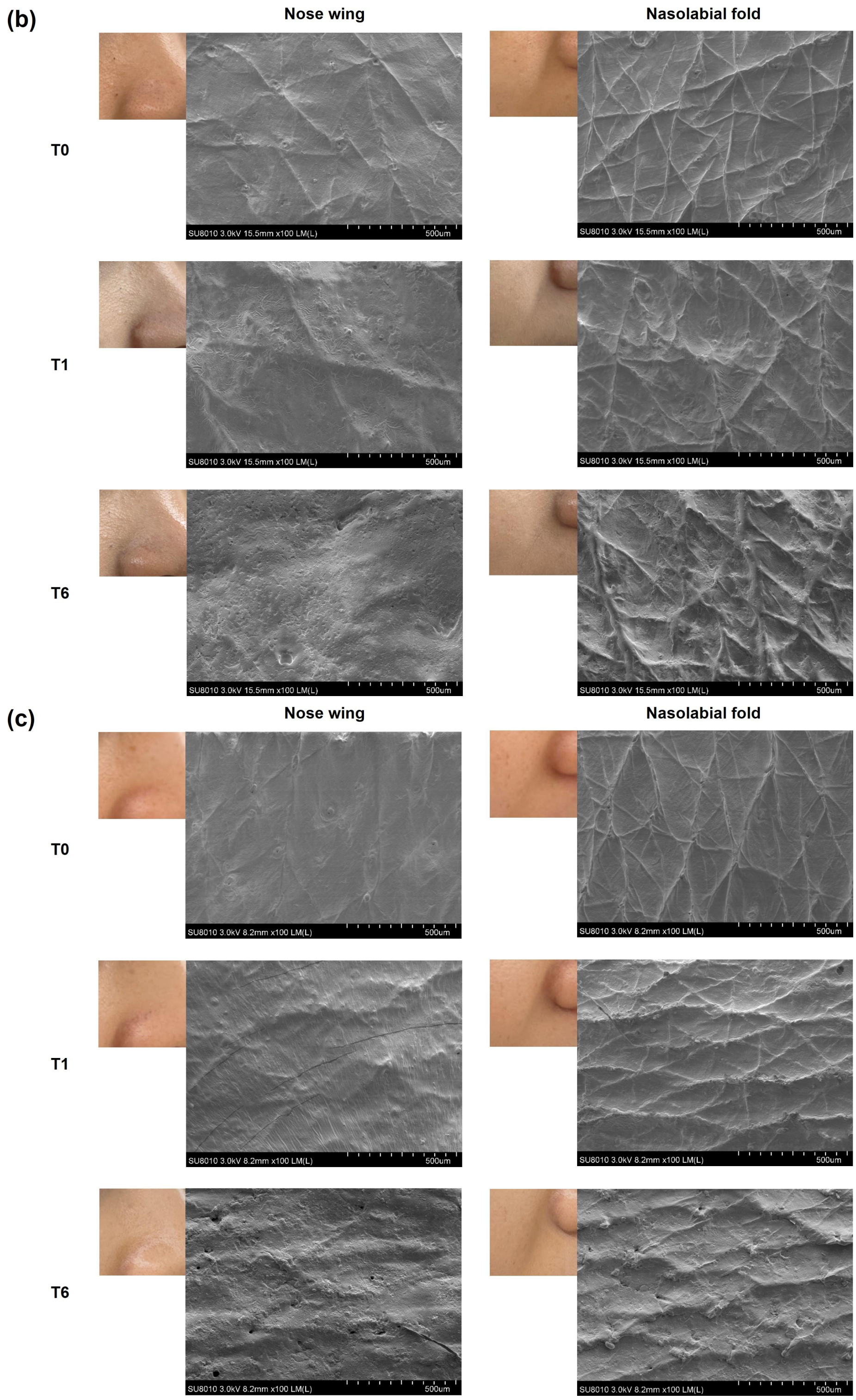


Figure 7. SEM images of skin replicas obtained from the nose wing and nasolabial fold areas applied with FL1 (a), FL2 (b) and FL3 (c).

SEM images revealed that the liquid foundation was evenly distributed on the skin surface immediately after application but became uneven after 6 hours, with possible powder accumulation and makeup removal. These changes in microstructure may arise from two factors. First, the secretion and infiltration of sebum could disrupt the uniform distribution of color powders in the foundation, causing certain color components (such as iron black and iron red) to float to the surface, which altered light refraction and reflection, ultimately leading to an uneven and mottled appearance. Second, the movement of facial muscles may cause the liquid foundation at the nasolabial folds to shift, resulting in uneven distribution of powders. Frequent mouth movements could lead to great accumulation of the foundation at the nasolabial folds and increase the likelihood of it falling off, forming a card powder phenomenon that made the nasolabial lines more prominent.

In conclusion, establishing a method for observing the microstructure of the foundation film can reveal whether powders, pigments, fillers and other ingredients in the liquid foundation are evenly distributed on the skin surface. This uniformity is crucial for providing consistent concealing effects and skin tone correction, and reducing makeup removal and uneven color due to ingredient aggregation. Additionally, this method can link observable makeup removal phenomena with microscopic changes such as powder movements, offering a deeper understanding of the interaction between the liquid foundation and the skin surface. What's more, microstructural observation can aid in researching the compatibility of liquid foundations with other cosmetics (such as the primer and loose powder), which is essential for the durability of overall makeup.

3.4 Moisture permeability measurements

In the daily life, especially in hot weather, the sweat is expected to penetrate the cosmetic film rather than smothered under the film to increase the breathability and comfort and reduce adverse reactions such as stuffy sweat and stuffy pox. The measurement is according to the moisture cup weighing method, that is, the two sides of the sample form a specific humidity difference at a certain temperature, and water vapor penetrate the sample into the dry side. By measuring the change of the moisture transmittance cup weight with time, the vapor transmittance of the sample can be calculated. Figure 8 showed the vapor transmittance of the samples. LF1 exhibited relatively better moisture permeability, with the vapor transmittance remaining at 450 g/(m^2·24 h). On the contrary, LF3 showed the worst moisture permeability, with the vapor transmittance remaining at 260 g/(m^2·24 h). This measurement provided a quantitative method for evaluating moisture permeability of the liquid foundation, having practical value for investigating the skin feel and long-lasting effect of the base makeup products.

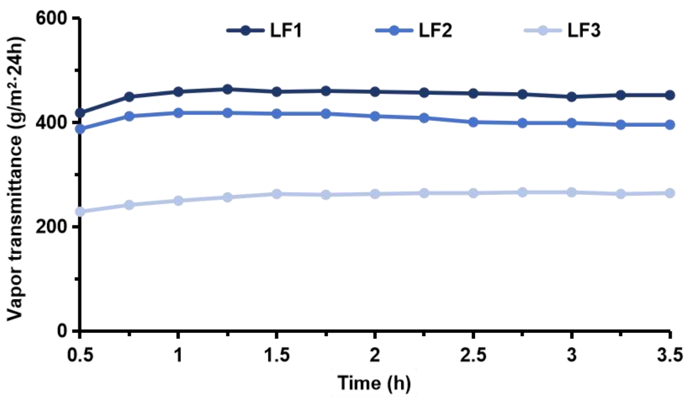


Figure 8. The moisture permeability of the liquid foundation.

3.5 Haze, gloss and color measurements

Figure 9 summarized the results of optical measurements for the liquid foundation. Haze is defined as the ratio of diffused transmitted light of the sample to the total transmitted light. High haze values of liquid foundations typically indicate greater abilities to scatter light, creating a softer, non-reflective effect on the skin. This property helps conceal skin imperfections and even skin tones while reducing shine on the skin's surface, making the makeup appear more natural and matte [19]. The haze values of three liquid foundations were all greater than 90%, indicating good soft focus and natural effects. Through haze measurements, the concealing effectiveness of liquid foundations can be quantified, which is significant for enhancing consumer satisfaction with foundation products and guiding formulation adjustments.

Gloss reflects the degree of light reflection on the material surface, and higher gloss values generally indicate shinier surface. The brightening effect of liquid foundations refers to its ability to enhance the skin's radiance and brightness after application, typically achieved by incorporating ingredients with reflective properties, such as mica and titanium dioxide [20]. The color difference (ΔE) characterized by the color difference value indicates how well the foundation matches the skin tone, which ideally should be as small as possible. Compared to the blank bio skin plate, the gloss and L^* values of both normal and freckle bio skin plates increased after applied with the liquid foundation, indicating that the samples could brighten the skin tone and improve dullness caused by blemishes such as freckles. LF2 demonstrated the best brightening efficacy, followed by LF3 and LF1. In addition, the ΔE values of LF2 on both normal and freckle bio skin plates were the largest in all the samples, indicating LF2 did not perform as well as LF1 and LF3 in balancing tone. The possible reason was that LF2 couldn't cover freckles effectively and evenly or its colour didn't match the freckle bio skin plate well, resulting in increased color difference. These results revealed that in vitro measurements could quickly compare performance differences of products, providing a convenient and time-saving method to accelerate the screening and refinement of formulations.

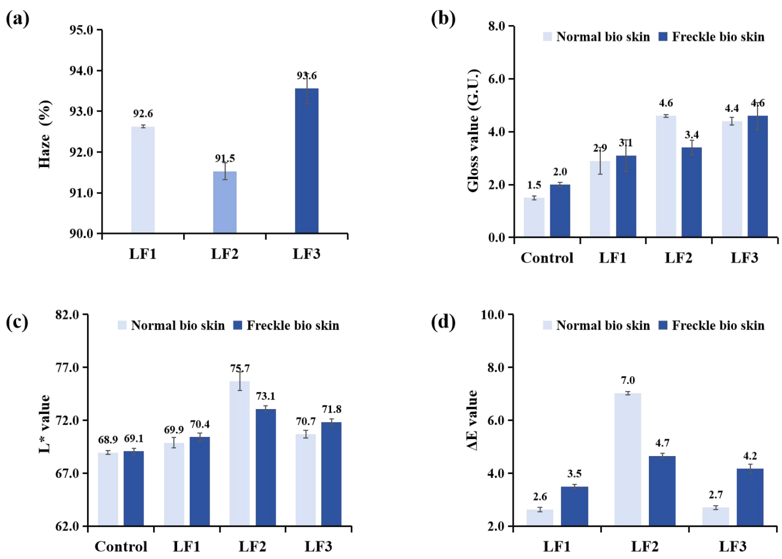


Figure 9. Haze values of liquid foundations (a) and gloss value (b), L* value (c) and ΔE value (d) of liquid foundations on normal bio skin and freckle bio skin, respectively.

4. Conclusion

The base makeup products are mainly designed to attenuate facial blemishes, such as pores, wrinkles and uneven skin tone. Consumers expect these products to have a natural, long-lasting and compatible makeup effect. Researching enterprises and personnels consequently need to develop scientific, detailed and complete methods to elucidate the properties of their products to convince the consumers, increasing the market value of the brand.

This study utilized contact angle measurements of water, artificial sweat and artificial sebum on normal bio skin plate to characterize the wettability of the liquid foundation. Changes in the surface morphology and structure of the liquid foundation film over time were observed microscopically, elucidating the effects of sebum secretion and facial muscle movements on the longevity and stability of the liquid foundation. Furthermore, the moisture permeability of the liquid foundation was assessed by the vapor transmittance tester, which is essential for using comfort. Finally, the makeup efficacy of the liquid foundation was evaluated in vitro using indicators such as haze, gloss, L^* and ΔE values. These measurements and results provided objective experimental standards for evaluating the makeup effects of foundation products and offered rapid guidance for the development of foundation formulations. However, whether these in vitro test results accurately reflect the performance of the products on actual human skin, and how to expand these findings to subjective perception evaluations require further explorations in the future.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Ikeda N, Miyashita K, Hikima R, et al., Reflection measurement and visual evaluation of the luminosity of skin coated with powder foundation. *Color Research & Application*. 39(1):45-55 (2012).
2. Batres C, Porcheron A, Latreille J, et al., Cosmetics increase skin evenness: Evidence from perceptual and physical measures. *Skin Research and Technology*. 25(5):672-676 (2019).
3. Fink B, Grammer K, Thornhill R. Human (Homo sapiens) facial attractiveness in relation to skin texture and color. *Journal of Comparative Psychology*. 115(1):92-99 (2001).
4. Chen G, Tan YM, Wang S, et al., Research on the intrinsic mechanism of the darkening of liquid foundation. *Skin Research and Technology*. 29(1):e13236 (2023).
5. Mittal KL, Etzler FM. Adhesion in pharmaceutical, biomedical and dental fields. Beverly: Scrivener Publishing LLC, 141-146 (2017).
6. Capra P, Musitelli G, Perugini P. Wetting and adhesion evaluation of cosmetic ingredients and products: correlation of in vitro-in vivo contact angle measurements. *International Journal of Cosmetic Science*. 39(4):393-401 (2017).
7. Jiang YW, Xu ZM, Qiu YC, et al., Evaluation of the antiwear-ability/scratch-resistance efficacy of makeup products by in vitro test method application. *Skin Research and Technology*. 29(8):e13420 (2023).
8. Pense-Lheritier, A.M. Recent developments in the sensorial assessment of cosmetic products: a review. *International Journal of Cosmetic Science*. 37(5):465-473 (2015).
9. Mittal KL, Bui HS. Surface science and adhesion in cosmetics. Beverly: Scrivener Publishing LLC, 379-400 (2021).
10. Nagaoka T, Kimura Y. Quantitative cosmetic evaluation of long-lasting foundation using multispectral imaging. *Skin Research and Technology*. 25(3):318-324 (2019).
11. Lee SY, Baek JH, Shin MK, et al., The quantitative analysis of spreadability, coverage, and adhesion effect after application of the base make-up product. *Skin Research and Technology*. 20(3):341-346 (2014).
12. Kim B, Lee J, Park S, et al., Method and analysis of color changes of facial skin after applying skin makeup. *Vision Research*. 209:108247 (2023).
13. Mittal KL. Advances in contact angle, wettability and adhesion. Beverly: Scrivener Publishing LLC, 193-222 (2018).
14. Niu J, Lin S, Chen D, et al., A fully elastic wearable electrochemical sweat detection system of tree-bionic microfluidic structure for real-time monitoring. *Small*. 20(11):e2306769 (2024).
15. Knox S, O'Boyle NM. Skin lipids in health and disease: A review. *Chemistry and Physics of Lipids*. 236:105055 (2021).

16. Xia MN, Wang XM, Liu YQ, et al., Relationship between skin parameters (darkness or thickness) and photoreaction of Chinese Han skin. *Cutaneous and Ocular Toxicology*. 31(4):306-311 (2012).
17. Askaruly S, Ahn Y, Kim H, et al., Quantitative evaluation of skin surface roughness using optical coherence tomography in vivo. *IEEE Journal of Selected Topics in Quantum Electronics*. 25(1):1-8 (2019).
18. Roh M, Han M, Kim D, et al.,. Sebum output as a factor contributing to the size of facial pores. *British Journal of Dermatology*. 155(5):890-894 (2006).
19. Choi SK, Yang YJ, Kim KN, et al., A study of the optical properties of cosmetics measured by polarized light goniophotometry. *Journal of the Optical Society of Korea*. 16(1):36-41 (2012).
20. Okamoto T, Kumagawa T, Motoda M, et al., Monte Carlo simulation of light reflection from cosmetic powder particles near the human skin surface. *Journal of Biomedical Optics*. 18(6):61232 (2013).