Silicones Offer Multifunctional Solutions for Hair Protection

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Abstract
The silicone family of materials is acknowledged for its sensory and functional benefits across hair care applications. These versatile materials offer a diverse range of benefits such as soft and smooth feel, detangling, shine enhancement, straightening, volume, anti-frizz, and the perception of moisturization. Initially formulated into hair care products for their conditioning benefits, silicones are today recognized as protective agents that aid color retention, protect against heat damage from curling irons and blow dryers, and provide strengthening properties to hair.

Dow Corning evaluated a variety of silicone materials for their ability to protect hair from color loss, heat aggression and frictional damage. Color protection was established using colorimetry evaluations with a spectrophotometer to record the influence of washes and UV exposure on color depth, anti-yellowing and loss of redness. Heat protection was determined using thermogravimetric analysis to evaluate moisture loss in hair during heat treatments, and differential scanning calorimetry was used to assess heat absorption by the hair. Hair strengthening was measured using a single-fiber tensile test method. Additionally, sensory evaluations supported validation of the conditioning benefits.

Keeping a wide view on global market expansion and predicting upcoming consumer and formulator needs helps create synergies between specialty silicones and innovation. A range of new silicone technologies is evolving, adapting to various hair types, environments, consumer preferences, evolving fashion, and formulating requirements. These technologies allow formulators to develop highly differentiated products with perceivable consumer benefits.

In today's fast-paced and competitive personal care market, fashion and good looks increasingly depend on evolving, high-performance technology, while consumers also look for ways to soothe, pamper and protect their bodies and their appearance. In part because hair vitality has become an expression of overall health, these trends are currently reflected in the hair care market. Demand for protective products is on the rise and a significant number of products currently offer protection claims. Out of 1,155 hair care products recorded in 2007 and early 2008, 31% claimed strengthening, 20% color protection, and 13% heat protection (1).

What is Hair Protection?
The global value growth of conditioners, hair coloring products, and shampoos outpaced the overall growth of the hair care segment from 2006 to 2007. Gillian Morris, director at Kline & Company, notes that during this timeframe and through 2008, hair protection has become an important functionality and label claim in many hair care products, from hair coloring to conditioning and styling. Through daily washing and styling regimens, hair becomes stripped of its moisture and natural oils and becomes brittle and dull. As Morris explains, hair that has been temporarily or permanently dyed is especially in need of protection to maintain condition and color. Environmental factors, stress, poor diet and hormonal changes also detrimentally affect the condition and thickness of hair (2). Other factors can include heated grooming tools, chlorine from pools, sea water, or even sweat. Some hair may be naturally prone to damage simply because of its very thin or fine nature.

In addition to protecting hair from potential damage, the concept of repair is also important. While it is not possible to truly "repair" damaged hair, it is possible to help restore its appearance of health and protect it from further damage. Results of hair damage include split ends, abraded and eroded hair cuticle and a resulting exposed cortex. This progressive damage leads to decreased moisture content in the hair, loss of capillary action—which limits the ability of hair to distribute natural oils—and a resulting dry feel. Hair can become stiff, dull, limp, and brittle, with added potential for frizz and inflexible curls.

To help prevent hair damage, one can minimize breakage by conditioning the hair shaft, a process that can help strengthen hair, protect it against heat aggression and prolong color. In general, the objective is to change the look of dull, faded, stiff, or limp hair to hair that has shine, smoothness, natural color, a soft and moisturized feel, manageability, and good volume.

However, consumer buying habits show the trend toward products offering hair protection doesn't tell the whole story. A range of additional expectations, some subtle, also influence product selection. In addition to pure performance, consumers look for a distinctive sensory experience, whether in terms of texture, feel during application, fragrance or visual characteristics. They also increasingly seek products with natural ingredients that connote freshness and purity, or those that indicate environmental responsibility on the part of the manufacturer or the consumer.

An array of specialty silicone materials can help formulators create hair care products that help protect hair, whether from environmental factors, color loss, heat associated with hair grooming—even the effects of daily combing and styling. These materials, in combination with other specialty ingredients such as natural oils and butters, waxes, and innovative thickening and emulsifying agents, can work together to offer synergistic effects in today's innovative hair care products.

Evaluating Hair Protection: Quantitative and Qualitative Methods

This paper describes a variety methods used by Dow Corning to evaluate the protective properties of silicones for hair care products. Quantitative methods were employed for all three primary protective strategies: hair strengthening, heat protection and color protection.

Hair Strengthening. A number of qualitative approaches are available for measuring hair strength, such as tensile testing, fatigue testing, microscopic analyses, light scattering measurements, and simple combing and counting, which involves combing a tress of hair and physically counting the number of hairs that break. Tensile tests involve applying a load to a hair fiber and measuring the amount of force. In this study, we chose single fiber tensile testing for several reasons. First, the method is both scientific and quantitative, and it is a recognized measure of hair strength (3-6). In addition, results are not affected by friction resistance; silicones are already known for reducing friction. Finally, in-house expertise already existed for other fiber materials, which was translated to measurements of single hair fibers.

Heat Protection. Understanding various parameters that affect hair exposed to heat can be very complex. Different test methods can measure different factors associated with heat damage. Thermodynamic studies measure heat flow through a material and can be used to demonstrate the importance of keeping moisture in hair. High thermal conductivity implies fast heat transfer. Because silicones have very low thermal conductivity, one might expect that because heat flow is slow, the presence of silicone along the hair shaft might reduce hair damage from heat (7). Heat protection can also be determined using thermogravimetric analysis (TGA) to evaluate weight (moisture) loss in hair during heat treatments. Differential scanning calorimetry (DSC) can be used to measure the thermal behavior of hair in terms of its heat absorption during the heat treatment. Heat flow is measured as hair is exposed to increasing temperatures from 40°C to 180°C.

Color protection. Colorimetry is widely used to measure changes in color after repeated shampooing and UV exposure of color-treated hair (8). A spectrophotometer allows the determination of three parameters that define color:

- L* values indicate the level of darkness (color intensity)
- a* values indicate the redness intensity (from green to red)
- b* values indicate yellowing level (from blue to yellow)

Qualitative observations were conducted to complement the quantitative protection studies. Scanning electroscopic microscope (SEM) photographs were used to evaluate the condition of hair with and without various treatments. Sensory evaluations were correlated to analytical results for parameters such as shine, feel and color intensity, to ensure consumer perceivable benefits.

Results of Studies

Silicones were initially incorporated into hair care formulations for their conditioning and perception of moisturization properties. Today, a variety of silicone materials are recognized for their essential sensory and functional benefits in a range of shampoos, conditioners, styling, and fixative products for hair. These versatile raw materials can be used to give a soft and smooth feel, aid detangling and combing, add shine, enhance straightening or encourage curl formation, provide bodifying effects, and act as anti-frizz agents.

In this study, a variety of silicone materials were screened as protective agents by aiding color retention, protecting against heat damage from curling irons and blow dryers, and/or providing strengthening properties to hair.

Hair strengthening. With their inherent conditioning ability, many silicones address the physical and environmental causes of hair damage. They can be especially useful in ethnic hair care products and products designed for weakened or damaged hair. In these cases, the ability of silicones to impart a perception of moisturization and control frizzy hair contribute to the overall conditioning effect.

As part of these evaluations, nonfunctional and functional silicones were evaluated for their ability to enhance hair strength, both dilute and in a leave-on hair care formulation, using single fiber tensile measurements. The work at 20% elongation was calculated and statistical comparisons were made between the untreated and treated fibers. Two silicones in particular demonstrated properties to enhance hair strengthening, making it less prone to damage and breakage:

- Silicone quaternium-16 (and) undeceth-11 (and) butyloctanol (and) undeceth-5
- Aminopropyl phenyl trimethicone

Figures 1 and 2 show samples treated with dilute leave-on and rinse-off silicone solutions exhibited higher work compared to the untreated control.

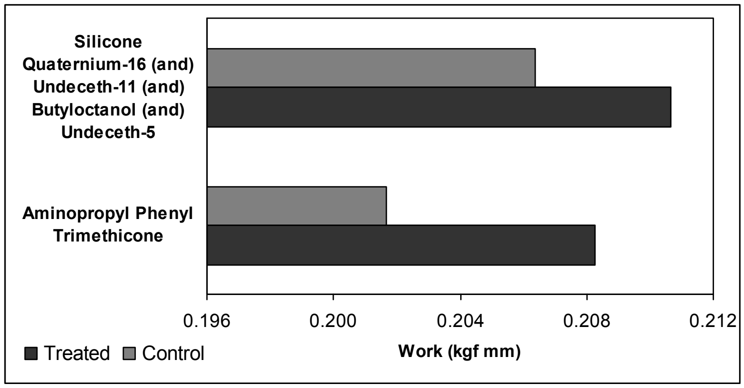

Figure 1. Work of elongation for hair fibers treated with leave-on dilute silicone solutions.

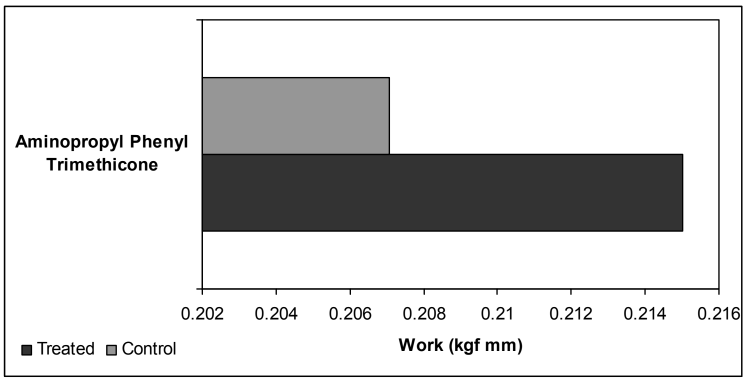

Figure 2. Work of elongation for hair fibers treated with rinse-off dilute silicone solution.

Two possible mechanisms may explain how a silicone film contributes to hair strength. It may protect the hair cuticle during elongation, and it may assist in sealing the hair cuticle, helping prevent moisture penetration into and out of the hair cortex to maintain an optimal moisture level for hair strength. The hair strengthening properties of these materials, combined with the other functional benefits of silicones for hair care, differentiate silicones from other traditional ingredients promoted for enhancing hair strength.

Heat protection. The moisture content of hair is crucial to maintaining its healthy appearance and feel. Processes such as blow drying and curling with hot irons can rapidly reduce hair moisture content below its normal level and can lead to damage. Hair dryers and other heated appliances first soften the keratin of the hair. If the appliances are too hot, they can actually cause the water in the hair to boil, forming minute bubbles of steam inside the softened hair shaft, weakening the fiber and potentially leading to total fracture. In general, silicones have good thermodynamic properties to help protect hair and maintain its moisture.

Analytical assessments using dynamic TGA were completed to establish the possible role silicones could play in reducing the loss of water from hair fibers. Hair tresses were treated with various silicones applied at a level of 0.125 g silicone per gram of hair. Treated hair was then subjected to various heating cycles in a nitrogen atmosphere. Heating occurred at a rate of 10°C per minute, ranging from 25 to 300°C. Figure 3 compares the results of hair tresses treated with three silicones vs. no silicone. All the silicones helped retain moisture in the hair over a broad temperature range, with the silicone quat microemulsion performing best.

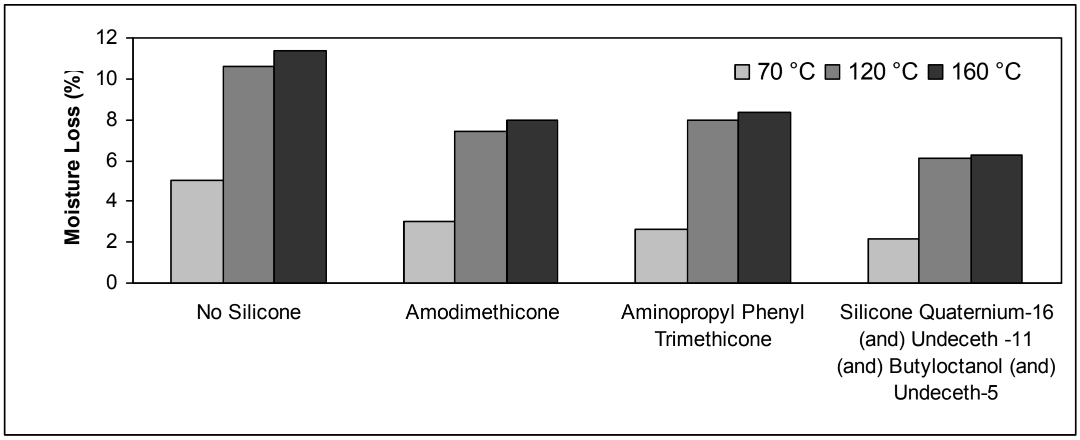

Figure 3. TGA studies illustrate moisture retention in hair.

In the DSC studies, all tresses treated with silicones allowed three times more heat to be absorbed. The silicone film on hair makes it more difficult for water to evaporate, and this retention of moisture translates to better heat protection.

As Figure 4 shows, lauryl PEG/PPG-18/18 methicone, divinyldimethicone/dimethicone copolymer (and) C12-13 pareth-23 (and) C12-13 pareth-3, and bis (C13-15 alkoxy) PG amodimethicone gave the strongest performance. The blend of cyclopentasiloxane (and) dimethiconol with cyclopentasiloxane also outperformed the control.

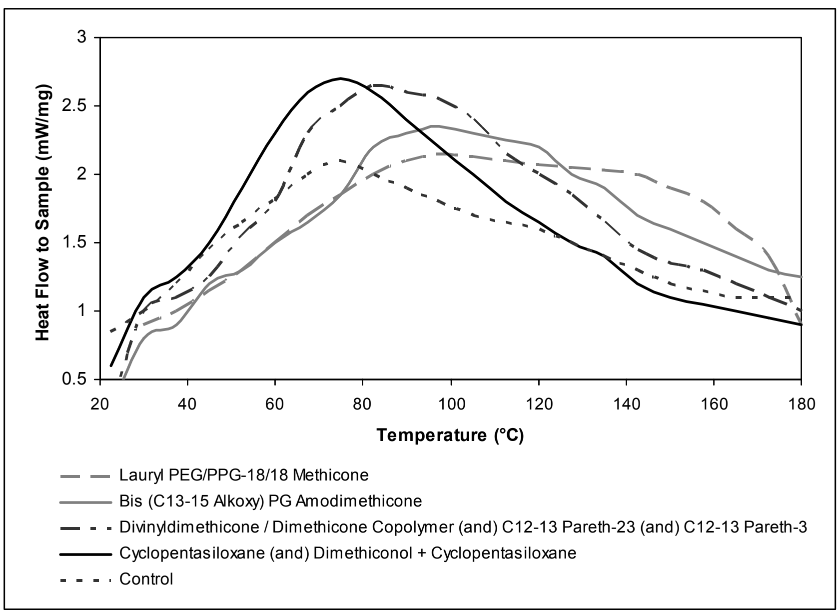

Figure 4. DSC results with various silicone materials.

Qualitative analysis using SEM helped validate the other heat protection studies. The SEM photographs of Figure 5 compare untreated hair and hair treated with neat aminopropyl phenyl trimethicone. After three thermal/mechanical stress cycles, the hair protected with silicone had a smooth, unabraded cuticle. In contrast, the untreated hair had a scaled appearance due to desquamation of the hair cuticle.

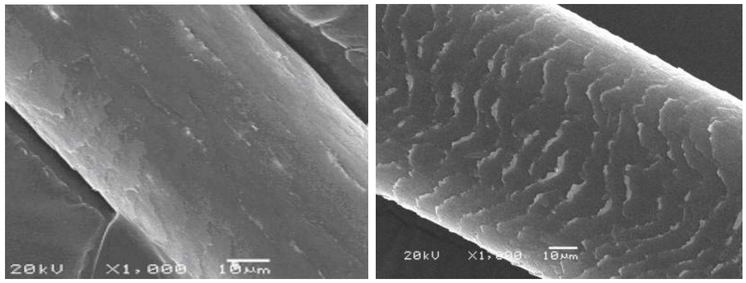

Figure 5. SEM photographs showing (left) treated and (right) untreated hair.

Sensory evaluations are another qualitative approach that supports quantitative studies. Silicones provide an improved sensory profile after heat treatments, particularly after a shampoo cycle. Sensory results of the tests were shown in two ways. Five individual attributes of dry hair (feel, combability, detangling, static formation and shine) were evaluated. A sensory index also was calculated based on an average of the five sensory attributes. The sensory index provides a good comparative measure of the overall conditioning of the hair.

Before shampooing, and with or without silicone treatment, sensory profiles of heat-treated hair were similar, and also better than hair that had not received the heat treatment. In other words, thermal treatments alone initially improved the positive sensory characteristics of hair, possibly because they temporarily flatten the hair cuticle. These results reflect a common observation: immediately after thermal treatment, hair typically feels better and is free of tangles, easier to comb and more shiny (Figure 6).

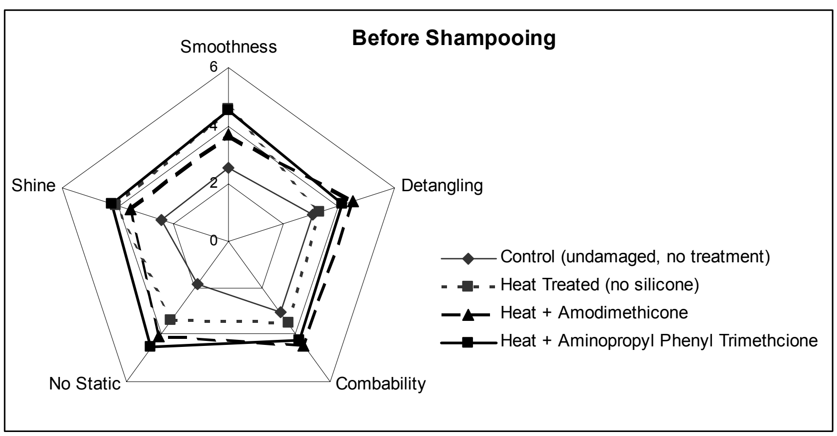

Figure 6. Sensory characteristics of dry hair (damaged vs. undamaged) before shampooing.

The difference becomes apparent after shampooing, when the consumer may realize that his or her hair is damaged. In this study, silicone-treated hair (with or without heat treatment) always had a better appearance than hair not treated with silicone (with or without heat), and thermal treatments clearly decreased the sensory profile of the hair tresses. After heat treatment and even one shampoo, hair not treated with silicone showed the effects of moisture loss and cuticle damage promoted by the heat treatment. However, on the tresses treated with silicone, positive sensory effects were sustained through three shampoos, showing that silicones provided protection from heat damage and improved the sensory profile of the hair tresses. As Figure 7 shows, tresses treated with silicones retained their positive sensory characteristics after shampooing, while the tress not treated with silicone did not. These studies suggest that silicones can protect hair during heat treatments and against the loss of positive sensory characteristics, even after shampooing.

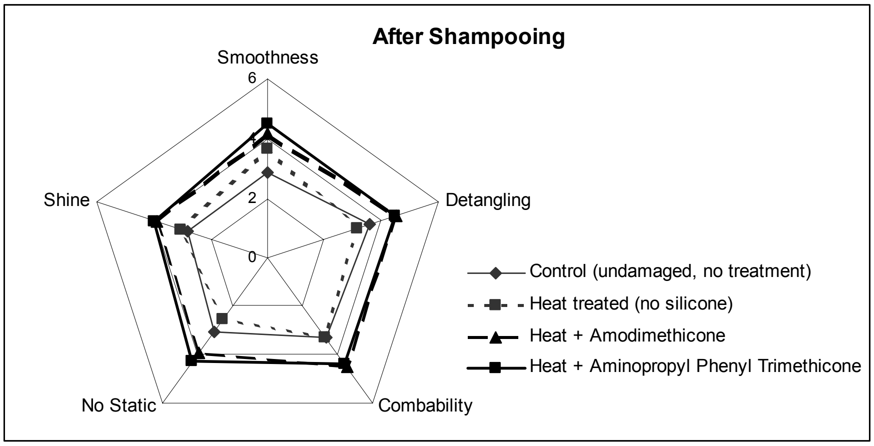

Figure 7. Sensory characteristics of dry hair (damaged vs. undamaged) after shampooing.

Color Protection. The use of hair colorants is growing on a global scale, and with that growth the importance of maintaining long term performance. Today's market is mainly composed of rinse-off conditioners and shampoos, and claims of color protection are linked to hair beauty, such as shine, softness and suppleness. Because of the prevalence of rinse-off products with color protection claims, tests were based on that product form. However, the consumer need for color maintenance is not fully fulfilled, and opportunity exists for a wider range of product forms that offer color protection. The potential for silicones to aid color retention was measured using a colorimeter/spectrophotometer to record the influence of washes and UV exposure on color depth, anti-yellowing and loss of redness. Twenty measurements were made per tress of slightly bleached hair, which shows the best color reproducibility when treated with a leading brand commercial permanent colorant. The impact on color loss of these tresses due to shampoo washes, rinse-off applications and UV exposure was studied.

Silicones used at a 2% active level demonstrate color protection properties when incorporated in rinse-off conditioner treatments. Figures 8-10 illustrate the ability of silicones to help maintain the three components of color as recorded with the colorimeter: L* for color depth, b* for yellowing and a* for redness.

The contribution of silicone to maintenance of color depth can be described by the following equation:

$$L^* (\%) = \{(L_t-L_o)*100/L_o\}_{control} - \{(L_t-L_o)*100/L_o\}_{silicone}$$

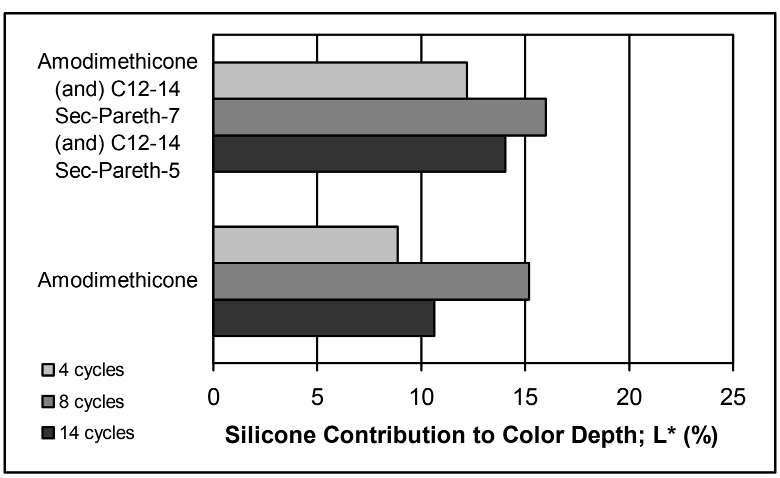

Figure 8. Percent reduction of color depth (L) for two aminofunctional silicones.*

The contribution of silicone to color maintenance in terms of anti-yellowing can be described by the following equation:

$b^* (\%) = \{(b^*_t - b^*_o)*100/b^*_o\}_{control} - \{(b^*_t - b^*_o)*100/b_o\}_{silicone}$

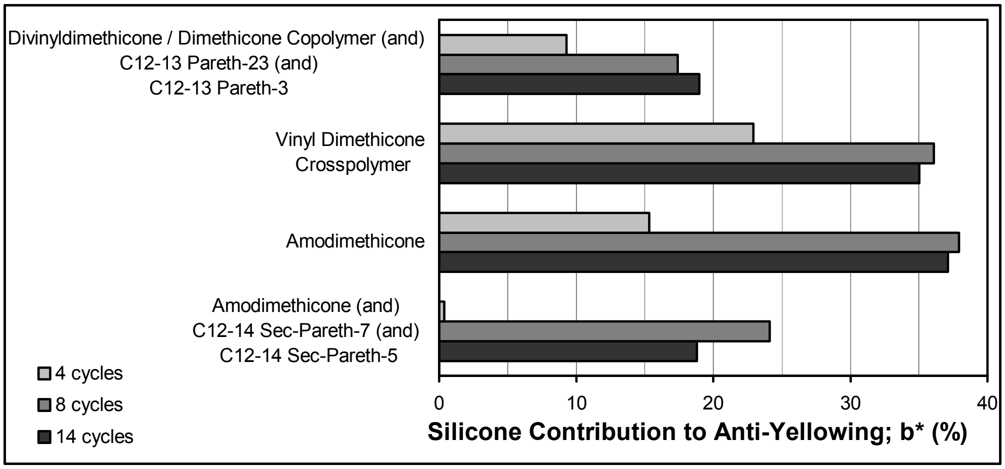

Figure 9. Percent reduction of b value (yellowing) for various silicone materials.*

The contribution of silicone to color maintenance in terms of loss of redness can be described by the following equation:

$a^* (\%) = \{(a^*_t - a^*_o)*100/a^*_o\}_{control} - \{(a_t - a_o)*100/a_o\}_{silicone}$

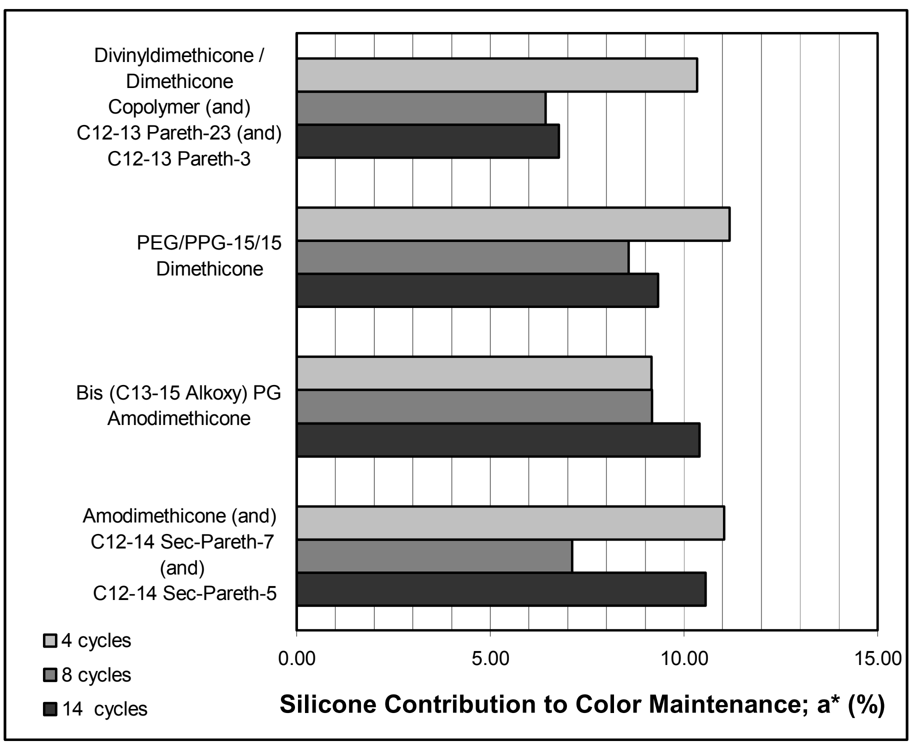

Figure 10. Percent reduction in loss of redness (a) for several silicone types.*

In a similar series of tests, colored hair treated with a rinse-off conditioner containing bis-isobutyl PEG/PPG-20/35/amodimethicone copolymer (and) cetyl ethylhexanoate (and) polysorbate 80 (and) butylene glycol shows the ability of this silicone emulsion to maintain redness. Figure 11 shows the a* value evolution with washes.

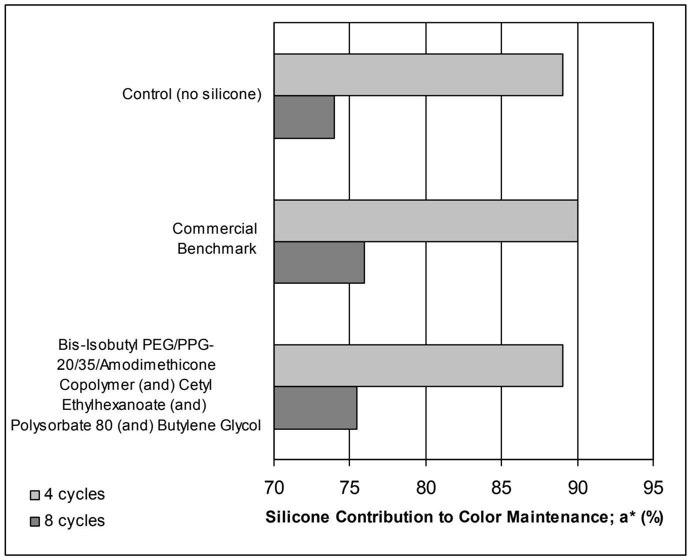

Figure 11. Percent reduction in loss of redness (a) for bis-isobutyl PEG/PPG-20/35/amodimethicone copolymer (and) cetyl ethylhexanoate (and) polysorbate 80 (and) butylene glycol.*

A sensory evaluation using 18 panelists also demonstrated that tresses treated with eight shampoo and conditioner cycles retained more red when bis-isobutyl PEG/PPG-20/35/amodimethicone copolymer (and) cetyl ethylhexanoate (and) polysorbate 80 (and) butylene glycol was used.

In another test, bis-hydroxy/methoxy amodimethicone also contributed positively to a* value (Figure 12). After eight shampoo and conditioner cycles on hair tresses, this silicone fluid had less red color loss than the control and matched the commercial benchmark at the 95% confidence level. A sensory evaluation using 14 panelists confirmed these results.

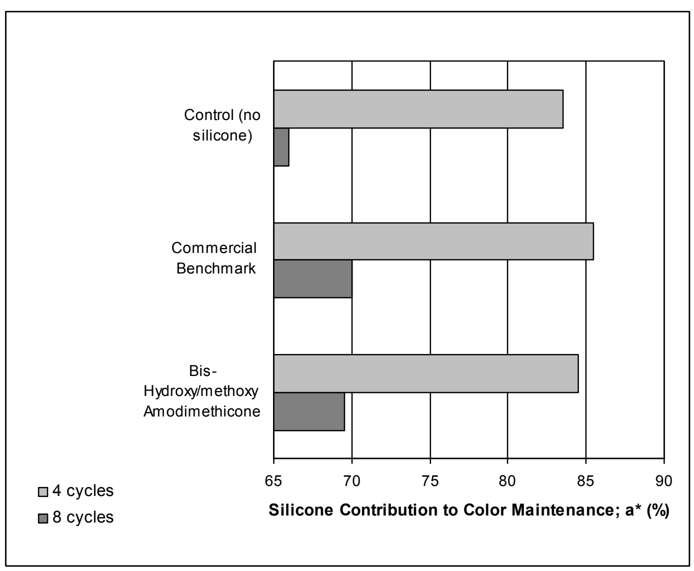

Figure 12. Percent reduction in loss of redness (a) for bis-hydroxy/methoxy amodimethicone.*

Additional tests have demonstrated the addition of silicone quaternium-16 (and) undeceth-11 (and) butyloctanol (and) undeceth-5, or amodimethicone (and) C11-15 pareth-7 (and) laureth-9 (and) glycerin (and) trideceth-12, can also improve color protection properties from rinse-off conditioners.

Table 1 summarizes the influence of silicones on color depth and color intensity.

Table 1. **Comparison of Color Improvement Using Various Silicones**

L* (darkness)	B* (anti-yellow)	A* (redness)
• Amodimethicone (and) C12-14 Sec-Pareth-7 (and) C12-14 Sec-Pareth-5 • Amodimethicone	• Amodimethicone (and) C12-14 Sec-Pareth-7 (and) C12-14 Sec-Pareth-5 • Amodimethicone • Vinyl Dimethicone Crosspolymer • Cyclopentasiloxane (and) Dimethicone Crosspolymer	• Divinyldimethicone / Dimethicone Copolymer (and) C12-13 Pareth-23 (and) C12-13 Pareth-3 • PEG/PPG-15/15 Dimethicone • Amodimethicone (and) C12-14 Sec-Pareth-7 (and) C12-14 Sec-Pareth-5 • Amodimethicone (and) C11-15 pareth-7 (and) laureth-9 (and) glycerin (and) trideceth-12 • Bis (C13-15 Alkoxy) PG Amodimethicone • Bis-isobutyl PEG/PPG-20/35/Amodimethicone Copolymer (and) Cetyl Ethylhexanoate (and) Polysorbate 80 (and) Butylene Glycol • Bis-Hydroxy/Methoxy Amodimethicone • Silicone Quaternium-16 (and) Undeceth-11 (and) Butyloctanol (and) Undeceth-5

Several hypotheses might help explain why silicones are good protective agents against color fading. Although most colorant does not penetrate the hair cuticle, a portion remains on the upper layers of cuticle and can easily be removed when hair is washed. When deposited on hair, silicone forms an external, homogeneous, water-insoluble film that helps color redeposit on the hair during washes.

In many applications, silicones act as a synergistic agent. It has also been suggested that a synergistic deposition mechanism between the colorant and the silicone can occur. This would lead to a higher deposition of the colorant in the presence of silicone when hair is washed.

Silicones have very low surface tension and help colorant spread on hair and form a homogeneous film. In addition, because of this spreading behavior, silicone may help the colorant further penetrate the hair cuticle.

Summary of Results

Based on the collection of studies, the following silicones showed potential for providing protective characteristics along with versatility in formulation for hair care products. Table 2 summarizes their protective properties.

- Aminopropyl phenyl trimethicone[1], a liquid amino phenyl silicone resin
- Bis-isobutyl PEG/PPG-20/35/amodimethicone copolymer (and) cetyl ethylhexanoate (and) polysorbate 80 (and) butylene glycol[2], an amino silicone polyether emulsion
- Silicone quaternium-16 (and) undeceth-11 (and) butyloctanol (and) undeceth-5[3], a 25% nonionic microemulsion of cationized aminofunctional silicone polymer
- Amodimethicone (and) C11-15 pareth-7 (and) laureth-9 (and) glycerin (and) trideceth-12[4], a microemulsion of an aminofunctional silicone polymer
- Bis-hydroxy/methoxy amodimethicone[5], an aminofunctional silicone polymer
- Amodimethicone[6], an aminofunctional silicone polymer
- Bis (C13-15 alkoxy) PG amodimethicone[7], an amino glycol silicone copolymer

Table 2. Protective Properties of Selected Silicone Materials

Material	Color Retention	Heat Protection	Enhanced Strength	Other Primary Benefits
Aminopropyl Phenyl Trimethicone		√	√	Long-lasting shine
Bis-Isobutyl PEG/PPG-20/35/Amodimethicone Copolymer (and) Cetyl Ethylhexanoate (and) Polysorbate 80 (and) Butylene Glycol	√			Moisturized feel
Silicone Quaternium-16 (and) Undeceth-11 (and) Butyloctanol (and) Undeceth-5	√	√	√	Volume
Amodimethicone (and) C11-15 Pareth-7 (and) Laureth-9 (and) Glycerin (and) Trideceth-12	√			Clear systems
Bis-Hydroxy/Methoxy Amodimethicone	√			Conditioning
Amodimethicone	√	√		Shine
Bis (C13-15 alkoxy) PG Amodimethicone	√	√		Clear shampoos, non-yellowing

Versatility for Formulating

Dow Corning has developed a variety of prototype formulations to illustrate how the benefits of tested silicones can be extended to formulations that can provide multifunctional, individualized properties for consumers who seek performance and protection, along with distinctive sensory characteristics.

The leave-in conditioner of Formulation 1 demonstrates a combination of silicones that may offer color and heat protection along with a soft feel and increased volume. The clear, water-based formulation is an added benefit for consumers who seek more natural appearing products. The formulation offers versatility for delivery as a spray or from the bottle.

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[1] Dow Corning® 2-2078 Fluid
[2] Dow Corning® CE 8401 Emulsion
[3] Dow Corning® 5-7113 Silicone Quat Microemulsion
[4] Dow Corning® CE-8170 AF Microemulsion
[5] Dow Corning® AP-8087 Fluid
[6] Dow Corning® 2-8566 Amino Fluid
[7] Dow Corning® 8500 Conditioning Agent

Formulation 1. Leave-In Conditioner (CPF 817)

Ingredient	% w/w
A	
Solubilizer (choice)	1.0
Fragrance	0.1
Helianthus annuus (sunflower) seed oil	0.1
B	
Water (*aqua*)	89.3
C	
Propylene glycol	2.0
Butylene glycol (1,3-butylene glycol)	3.0
Silicone quaternium-16 (and) undeceth-11 (and) butyloctanol (and) undeceth-5 (Dow Corning® 5-7113 Silicone Quat Microemulsion)	2.0
Preservative (choice)	0.5
Yellow 6 (FD&C Yellow 6 W082, LCW Sensient)	q.s.
PEG-12 dimethicone (Dow Corning® 193C Fluid)	2.0

Procedure: Combine A. Add B to A with mixing. Add C with mixing.

A variation on Formulation 1, Formulation 2 becomes a styling mousse with the addition of a water-based styling agent.

Formulation 2. Styling Mousse (CPF 818)

Ingredient	% w/w
A	
Solubilizer (choice)	2.0
Fragrance	0.5
B	
Water (*aqua*)	83.0
C	
Cocamide DEA	2.0
PVP/VA copolymer	2.0
Silicone quaternium-16 (and) undeceth-11 (and) butyloctanol (and) undeceth-5 (Dow Corning® 5-7113 Silicone Quat Microemulsion)	4.0
Preservative (choice)	0.50
Cocamidopropyl betaine (Dehyton, Cognis Corporation)	2.0
PEG-12 dimethicone (Dow Corning® 193C Fluid)	1.0

Procedure: Combine A ingredients. Add B to A with mixing. Add C with mixing.

Formulation 3 was designed to protect or restore the beauty of curly hair. It can be used as a leave-on treatment if strong conditioning is required, or as a rinse-off conditioner. Waxes, natural oils and silicones provide complementary benefits. Studies described in this paper demonstrate that the addition of bis (C13-15 alkoxy) PG amodimethicone can provide color protection properties to hair.

Formulation 3. Hair Treatment Cream for Curly Hair (CPF 1028)

Ingredient	% w/w
A	
Ceteareth-20 (Eumulgin B2, Cognis Corporation)	0.75
Behentrimonium methosulfate (and) cetearyl alcohol (Incroquat Behenyl TMS, Croda Inc.)	1.50
Cetearyl alcohol (Lanette Wax O, Cognis Corporation)	3.00
Glyceryl stearate (Cithrol GMS, Croda Inc.)	3.00
Prunus amygdalus dulcis (sweet almond) oil (Lipovol ALM, Lipo Chemicals)	2.00
B	
Water (*aqua*)	84.85
C	
Bis (C13-15 alkoxy) PG amodimethicone (Dow Corning® 8500 Conditioning Agent)	3.00
D	
Phenoxyethanol (and) methylparaben (and) butylparaben (and) ethylparaben (and) propylparaben (and) isobutylparaben (Dragocide Liquid 2/060140, Symrise)	0.40
E	
Citric acid	q.s.

Procedure: Heat A ingredients to 70-75°C. Heat B ingredients to approximately 80°C. Add B to A with mixing. Mix until cool. Add C and mix. Add D and mix. Adjust pH to 4.0-4.5 with E.

Conclusions

The silicones described here provide a range of hair protection properties, which when combined with their functional and sensory benefits offer greater flexibility for formulators. Additionally, these specialty silicones can be used with organic materials, including natural oils, butters or waxes to provide synergistic effects for conditioning, shine and sensory properties.

While considering global market needs based on hair types and conditions, ethnic preferences and evolving fashion trends, these silicone materials offer a wide range of innovative technology and formulation concepts for hair protection. Information from our studies can also serve as a screening tool to help formulators determine which silicones are most appropriate for specific applications or chemistries (9). The result can be shorter test times and faster development of highly differentiated products to protect hair and help create and maintain its healthy appearance.

References

1. Dow Corning survey based on Global New Products Database, Mintel Group (2007, 2008)

2. Personal communication, Gillian Morris, director, Kline & Company (June 2008)

3. T Scharfeld, C D'Arrigo, and KH Lim, A single hair fiber tensile tester for operation under a scanning electron microscope, Massachusetts Institute of Technology, 1-5

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