"Explorations of consumer relevant testing of textured hair"

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1. Introduction

Analytical studies have reported that hair with different shape and curl level do not differ significantly in their amino acid and protein composition, but hair from African origin has been found to contain higher level and more differentiated lipid composition than straighter hair types [1-4]. The morphological variations characterising different hair shapes and curl levels representing different geo-racial origins have been identified: straighter hair has more circular and larger cross-sectional area, whilst curlier hair has elliptical and generally smaller cross-sectional area [5]. Single fibre morphology and geometry affects the hair assembly behaviour relevant to how people manipulate and manage their hair using cosmetics. At the core of many hair assessment techniques is seminal work elaborating on the impact of single fibre characteristics on hair assembly, and outlining combing, flyaway, limpness, body, style retention and manageability as key dimensions of hair assembly quality [6,7]. Of these, the instrumental combing ease test is considered to be an objective and sensitive reflection of the cuticle integrity and the lubrication delivered by hair conditioning products [8].

The variations of wet and dry combing profiles of straight hair types are explained well by cuticle and fibre swelling, fibre cohesion and distance travelled by the comb [9-11]. However, it is understood that, for curly and textured hair, the curvature effect dominates the measurements unlike in straighter hair types. The variety of curvature and the difficulty with preparing adequate experimental tresses contribute to the persistent gap in the combing assessment of highly textured hair. More recently, adaptations of instrumental testing parameters to textured hair characteristics have been reported [12-14]. Friction measurements are considered relevant and complementary to combing tests of straight hair, but less so for curlier hair types. The coefficient of friction (COF) reflects the combined impact of single fibre shape and size, cuticle profile, product and the presence or lack of fibre alignment. In the case of the most textured hair, these effects are likely to be further compounded by the difference in the 3D shape of the hair tresses, as flat presentation is the norm for friction measurements in straighter hair, something that cannot be achieved with textured hair bundles without altering the fibre natural form by stretching. Thus, hair tress stiffness is another complementary test providing more holistic understanding of textured hair behaviour. For very curly and textured hair types, the subjective perception of hair softness is somewhat merged with other subjective experiences such as hair dryness [14]. Technical tress stiffness tests of hair were originally validated for the efficacy assessment of fixative polymers on hair and applied to straight hair exclusively. However, the principle of the three-point cantilever test was reported as a method for assessing straight hair suppleness and textured hair assembly too [13].

Oils and butters have been commonly used for combined scalp and textured hair management for centuries, as they are hailed to reduce scalp dryness and irritation as well as to protect and improve the hair condition. Oil-soluble ingredients remain of interest to hair science today due to their capacity to penetrate the cuticle and cortex of hair. Moreover, the positive effects of these materials on textured hair are anecdotally promoted to be of particularly high significance for combating its reported fragility. As oil and other lipophilic actives are applied and reapplied to textured hair, the rheological profile of the formulations is also important, in addition to the sensorial and styling benefit they confer to the hair.

Objective*.* This project applies a novel interdisciplinary methodology for addressing the needs of consumers with textured (type 4) hair, the related rheological properties of leave-in emulsion-based formulations and the instrumental tress-based assessments of their efficacy. Two converging parallel studies were conducted:

- consumer study: exploring the consumer goals.
- experimental study: product characterisation and hair assembly testing techniques.

2. Materials and Methods

2.1. Consumer study

<u>Participants and survey platform.</u> One hundred and twenty-three (n=123) participants who had self-identified as having a natural curl type 4 hair, according to a popular (non-scientific) hair typing system, were surveyed (Qualtrics, USA). The recruitment of participants from the UK and USA took place via Prolific Academic (Prolific Academic Ltd, UK). The survey instrument that the participants filled in comprised a taxonomy for exploring curly and textured hair goals (aesthetic, haptic, practical and emotional), haircare practices, product choices and a Hair Esteem (HE) index, reported previously [14].
<u>Consumer study statistics.</u> The survey data was analysed applying explorative statistics using StataSE 17.0 (StataCorp, USA).

2.2. Experimental study

<u>2.2.1 Formulations</u>
A non-ionic emulsion containing an emollient identified in pilot studies as elucidating curl type 4 hair benefits was formulated, as well as a control vehicle formulation (Table 1).
<u>2.2.2. Formulation characterisation methods</u>
Texture analysis was conducted using a TA.XT Plus Texture Analyser (Stable Micro Systems, UK) equipped with a 45° Perspex male–female cone fixture. All measurements were carried out in quintuplicate at a controlled temperature of 23.0 ± 0.1 °C. Key parameters obtained from the force–distance curves included: peak firmness (g), work of shear (g·s), stickiness (g), and work of adhesion (g·s).

Rheological analysis was conducted with Thermo Sientific™ HAAKE™ Mars™ iQ Air rheometer (Cole-Parmer, UK), with a cone (C35 2°/Ti) – plate geometry. All tests were performed in triplicate at a controlled temperature of 23.0 ± 0.1 °C. Flow properties were tested via shear rate sweep and structural breakdown via hysteresis area. Viscoelastic properties were tested via oscillatory methods (amplitude sweep and temperature sweep within the linear viscoelastic region).

Table 1. Control and Active formulations

			Control	**Active**
Phase	**INCI**	**Trade Name, supplier**	**w/w%**	
A	Cetearyl Alcohol	Surfac CS (Surfachem, UK)	5.0	5.0
	Ceteareth-20	Eumulgin® B2 (BASF, UK)	2.0	2.0
	Triolein	AlgaPūr™ (Lubrizol, USA)	0.0	5.0
B	Aqua	Deionised water	89.5	84.5
	Glycerin	Glycerin (Phoenix Products, UK)	3.0	3.0
C	Phenoxyethanol, Methylparaben, Ethylparaben, Propylene Glycol, and Ethylhexylglycerin	Azelis, UK	0.5	0.5

<u>2.2.3. Hair tresses</u>

Type 4 hair without history of heat and chemical damage was sourced from two donor women in South Africa. The hair was bulked, and ten tresses produced with defined weight (Mean=0.93g, Median=0.9g, Mode=0.9g) and length (Mean=58mm, Median=60mm, Mode=60mm).

<u>2.2.4. Tress testing.</u>

The tresses were firstly tested untreated, and then after one and four consecutive Control formulation re-applications. Following a controlled and thorough stripping wash, each tress was retested after one and four applications of the Active formulation. 1 g of the leave-in treatment formulation (Control or Active) per 1 g of dry hair were applied to each tress with controlled massaging. In keeping with the consumer study results, before each round of product application, each tress was re-wetted with water sprayed from a defined distance (controlled quality). The product application was done incrementally, by small amounts being thoroughly massaged with gloved fingers onto the hair and repeating this until the full dose per tress was used. Hair was allowed to dry before testing or product replication.

<u>Combing</u> was performed using fibra.one (Dia-Stron Ltd, UK). In this test, the treated, dried hair was rewetted with water spray before combing was conducted. Each tress was tested three times with five combing runs per test thus generating fifteen values for the work of combing per tress per timepoint and condition.

<u>Friction</u> was performed on dry hair with fibra.one (Dia-Stron Ltd, UK) by applying three friction cycles per tress. The Coefficient of Friction (COF) of the root-to-tip movement values were extracted, averaged per tress and used for further analysis.

A three-point cantilever bending test was performed on dry hair using the TA.XT Plus Texture Analyser / Hair Stiffness Rig (A/3PBH) (Stable Micro Systems, UK). Stiffness values generated by the Exponent software (Stable Micro Systems, UK) were extracted for further analysis.

Statistical analysis. All data was first examined manually for outliers resulting in removing two friction cycle values. As data distribution did not meet the assumptions for parametric statistics, the sign test was applied, determining whether the direction of the median paired differences between two conditions are statistically significant. The null hypotheses were that the median of paired differences between tested conditions equalled 0.5, $p \leq 0.05$ was considered statistically significant. All statistics were conducted using SPSS (IBM, USA).

3. Results

3.1 Consumer study

The participants in the sample were on average 39.1 years old (range 21 to 76 years). 78% of them self-identified as Black, 12% - White, 7% mixed and 3% were of another ethnicity. Several associations of relevance to the testing method emerged. The four hair goals (aesthetic, haptic, practical and emotive) were significantly positively associated with relying on seeing and sectioning hair during the styling process. Several associations between hair goals and product choices were observed too: the number of different products used in a week was significantly positively associated with practical goals, emotive goals and hair esteem. Associations between the various reported hair practices and product choices were identified. Relying on feeling during the styling process was positively associated with wetting hair prior to styling. Wetting hair prior to styling was also positively associated with hair sectioning. Relying on seeing during the styling process, on the other hand, was positively associated higher number of different products participants used in a week. In summary, the findings about multiple product applications between washes, the hair wetting prior to product reapplication and hair sectioning during styling were considered pertinent to defining the hair testing methods in order to align them closer to the consumer behaviour.

3.2. Formulation characterisation

Texture analysis. The Active formulation exhibited overall higher textural parameters compared to the Control. Therefore, the Active is a firmer product with superior adhesive properties that may also require more energy to spread on application. Table 2 illustrates the difference in results for the two tests applied.

Table 2. Results from the texture analysis tests. Values are average (n = 5) +/- standard deviation (SD).

Textural Parameter	Control	Active
Firmness (g)	121.4 +/- 10.8	184.0 +/- 13.8
Work of Shear (g s)	105.3 +/- 7.8	170.5 +/- 13.7
Stickiness (g)	135.4 +/- 13.8	219.7 +/- 15.5
Work of Adhesion (g s)	34.5 +/- 1.8	57.5 +/- 3.7

Viscosity. Both formulations exhibited a decrease in viscosity with increasing shear rate, indicating shear-thinning behaviour with Active formulation mainting consitently higher viscosity across all shear rates.

Amplitude sweep test. The storage modulus (G′) and loss modulus (G″), representing the elastic (solid-like) and viscous (liquid-like) behaviour of the formulations respectively, were measured across increasing strain amplitudes. For both formulations, G′ had higher values than G″ within the Leaneir Viscoeleastic Region (LVR), indicating dominant solid-like behaviour under small deformation forces. The crossover point, where G′ equals G″ and the material transitions to more fluid-like behaviour, occurred at 2.0% ± 0.9% strain for the Control and 1.0% ± 0.5% for the Active formulation. Although the Active yielded at a lower strain, it exhibited almost doubled G′ throughout the LVR compared to the Control, suggesting stronger internal structure. This combination, high G′ but lower crossover strain, indicates that the Active formulation could present an imporved balance between structural stability at rest and ease of deformation under applied force, which is desirable for a leave-on conditioner application.

Hysteresis area. During the upward ramp, both the Control and Active formulations exhibited a decrease in viscosity with increasing shear rate, confirming typical shear-thinning behaviour. Under constant high shear (300 s^{-1}), the viscosity reached a minimum, as expected. During the downward ramp, the viscosity partially recovered, not returning to its original values—suggesting time-dependent mechanical recovery properties. Shear stress was plotted against shear rate to generate a hysteresis loop. The area between the upward and downward ramp curves quantifies the energy lost to structural breakdown. This area serves as a relative measure of thixotropy, where the greater the difference, the more pronounced the structural breakdown of the formulation. Both values of calculated difference were positive, confirming structural breakdown. However, the Control formulation exhibited substantially higher structural breakdown, as indicated by its larger hysteresis area of 184.1 Pa s, and less able to recover after shear. In contrast, the Active had lower hysteresis area of 26.0 Pa s.

Temperature sweep test.
Both formulations exhibited G′ > G″ throughout the tested range, indicating dominant elastic (solid-like) behaviour and suggesting structural stability under thermal fluctuations (Figure 2). The storage modulus (G′) decreased between 4 – 23 °C, indicating structural softening, likely due to the partial softening of cetearyl alcohol and ceteareth-20 or any crystalline structures resulting from their self-assembly, which are known to undergo thermal transitions in this range. In contrast, G″ (loss modulus) remained relatively stable, suggesting limited change in the viscous response. Above 25° C, G′ plateaued for the Active formulation, maintaining consistent elasticity up to 50°C (Figure 2)

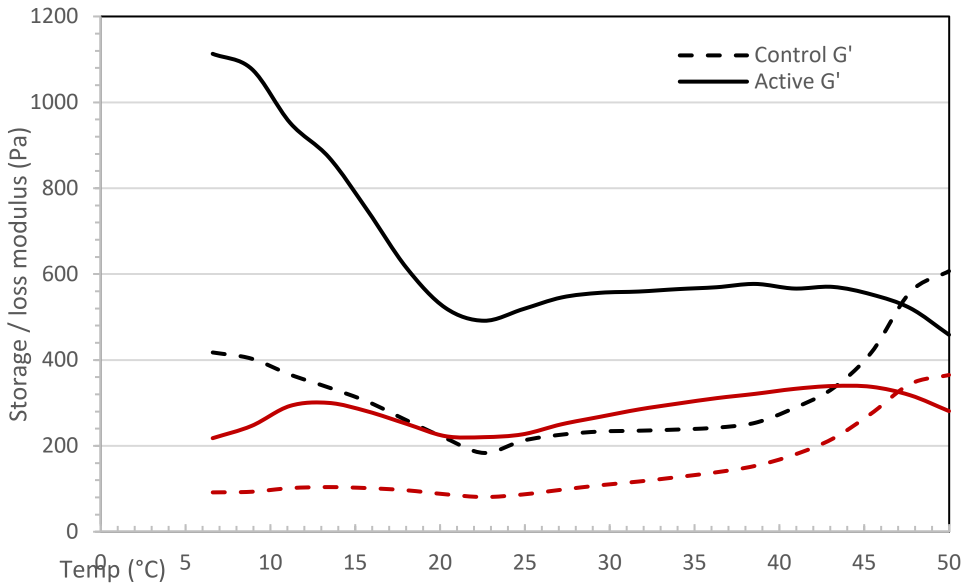


Figure 1. Representative G' and G" as a function under increasing temperature, constant strain 0.2% and frequency 1 Hz.

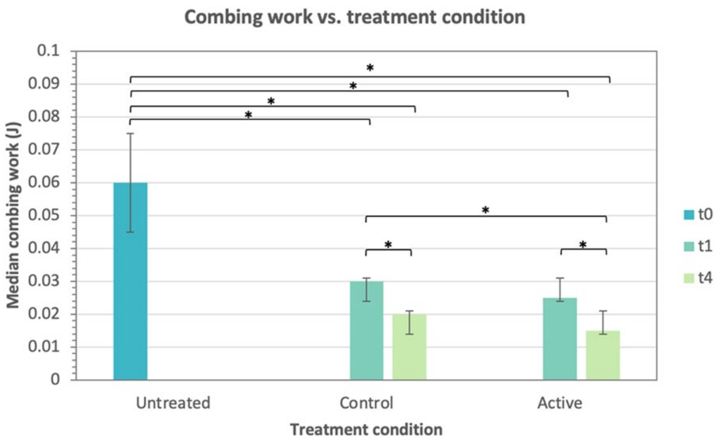
3.3. Hair tress tests

The medians and standard deviations of all conditions for wet combing, dry friction and three-point bending tests are reported in Table 3.

Table 3: The medians and standard deviations for all instrumental tress measurements

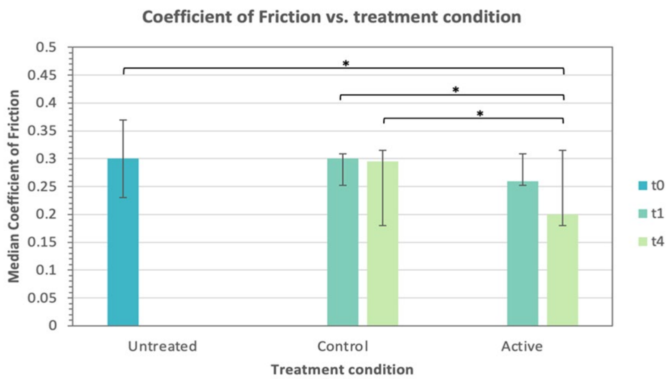
Condition	Combing work (J)		Coefficient of Friction (nu)		Stiffness (g)	
	Median	**Std. deviation**	**Median**	**Std. deviation**	**Median**	**Std. deviation**
Untreated	0.060	0.015	0.30	0.069	13.9	3.67
Control t1	0.030	0.008	0.30	0.068	9.80	3.57
Active t1	0.025	0.005	0.26	0.062	11.8	4.74
Control t4	0.020	0.010	0.30	0.052	8.93	2.53
Active t4	0.015	0.005	0.20	0.067	17.0	6.22

Wet combing. There were statistically significant median decreases in combing work between all conditions other than between t1Control and t1Active treatments and between t4Control and t4Active treatments (Figure1). Compared to the untreated tresses, one application of Control resulted in a 50% median decrease in combing work, whereas one application of the Active product resulted in a 58% decrease.



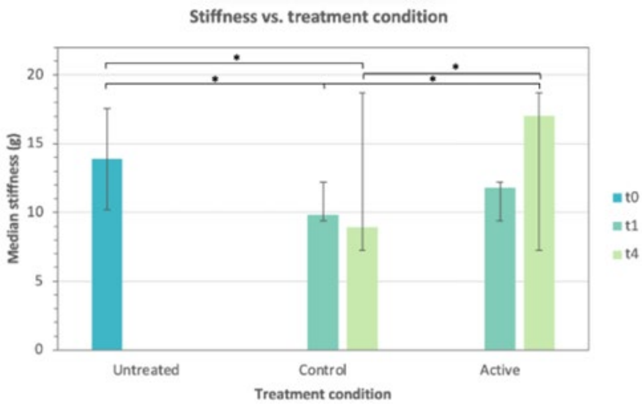
In comparison, four consecutive applications of the Control product resulted in a 67% decrease in median combing work compared to the untreated tresses, and the same amount of the Active resulted in a 75% decrease. Compared to one application of the same product treatment, four applications of Control decreased median combing work by 33%, whereas the same amount of Active resulted in a 40% decrease.

Figure 2. Results from the combing test, * denotes $p<0.05$



Friction. In comparison with untreated hair and one application of the Control formulation, four Active formulation applications reduced the COF by 33%. Four Active applications also elucidated 34% COF decrease in comparison to four Control applications. In summary, the Control did not impact the hair friction, but cumulative application of the Active elucidated a decrease in COF.

Figure 3. Results from the friction test, * denotes $p<0.05$



Three-point bending. The Control decreased stiffness in comparison with untreated hair after one application by 29% and multiple applications by 36% respectively, whilst multiple applications of the Active increased stiffness of hair in comparison to t1Control by 73% and t4 Control by 90% respectively.

Figure 4. Results from the stiffness test, * denotes $p<0.05$

4. Discussion

The consumer data analysis highlighted that the higher the importance the hair goals to the individual is, the more likely they were to section their hair. There could be various justification for sectioning hair and one of them reasonably could be to apply the product more thoroughly and evenly which returns perceivable goal related benefits. Hence, the treatment protocol and the result interpretation were contextualised to the practice of hair sectioning. Sectioning hair was also linked to more frequent product use and wetting hair prior to product application hence these practices were incorporated into the testing protocol. Multiple product reapplications between washing suggest that the consumer experiences the need to refresh style and, in turn, the need to consider product accumulation effects when testing for efficacy.

The product dosing in the test was high and not representative of the quantities that a consumer would use. However, this was an exploratory study seeking to establish the direction of product effects and to inform methodological development, hence this dose was deemed acceptable. Spraying the hair wet before applying a leave-in product was an important consideration too, as it is known that water decreases the curvature of textured hair. Whilst this step did not cause a visual change in the curl level (as water dosing was not so high), it could assist the application of the emulsion product by lowering the surface tension of the hair surface and thus easing its wetting by the emulsion with an external water phase. It could be also hypothysed that the multiple wetting and product reapplication procedure would have increased the surface coverage of the hair by the product via product accumulation. Thus, the extensive texture and rheology analysis could be of value to understand how the product might behave on the hair surface.

For the purpose this project, a nonionic formulation and active were selected, so that electrostatic-based wet conditioning was eliminated from the investigation, and so were high dry lubrication conditioning ingredients such as silicones and fixative polymers. Instead, a lipophilic active (triglyceride) was chosen, based on preliminary work comparing the impact of such ingredients on straight vs textured hair. Moreover, the rheological investigation allowed for easy differentiation of the Active impact, thus supporting also hypotheses in relation to the hair tress result interpretations.

Both formulations are shear thinning suggesting that the application process would be efficient in spreading the products on the hair. Rinse-off and leave-on hair conditioning products require such rheology in order to cover the substantial surface area presented by the hair assembly. Although the Active demonstrated higher values than Control, it is likely that in consumer context of spreading the product on the hair, this difference is insignificant in terms of the surface area and thinness of the segments of product film generated on the hair surface.

The lower structural breakdown of the Active product is aligned with its substantially higher stiffness observed via the texture analysis and suggests that it may retain higher structure following the application. Thus, if in sufficient quantities and coverage, the Active product may impart a fixative effect, versus surface lubrication alone.

The three tress test testing methods highlight that that testing textured hair requires consideration for the statistical analysis possible. To ensure test reproducibility and statistical relevance, more work on the methods is needed. However, as with other test, it is important not to compromise their consumer relevance for the purpose of improving statistical results. In this context, directional product effects are an informative starting point.

The testing methods applied in the study had specific elements of direct relevance to the reported consumer behavior and goals. The results suggest that the tests results could be complemented by the formulation's texture and rheological analysis. The combing of wet textured hair was selected as a test as previous studies suggest that dry hair combing is not common due to high combing forces. In these tests single and cumulative product application effects were statistically significant in causing a directional reduction in work of combing. Higher product quantities resulting from the multiple applications magnified the effect in comparison to a single product application. Hair detangling/combing is considered a practical goal; hence emulsions appear efficacious for achieving this goal. The directional change between treatments also suggests that the ingredient effect is detectable on textured hair. Although, combing is less frequent in individuals with textured hair, in line with the consumer practical goals, it is important that leave-in products offer such benefit. Dry friction is more akin to the experience of stroking dry hair thus related to the haptic goals. Only multiple Active applications appeared to outperform control thus suggesting that lipophilic actives have the potential to alter the surface profile of textured hair towards making it smoother hence have the potential to improve its haptic profile. The higher quantity of lubricating active is eliciting reduction of friction thus suggesting that appropriate rheological profile allowing for good even hair surface coverage is advantageous. The other dimension of haptic goals of curly hair is hair softness. The three-point bending test suggested that multiple Active application cause the hair to become stiffer. This can be explained via the higher firmness of the Active formulation measure via the texture analysis which similarly to the three-point bending test applied a load to the product over a small surface area. Furthermore, the Active's capacity to retain structural integrity under shear could be adding to the hair bulk's overall stiffness. It is of relevance to continue to explore the relationship of these results further, over more varied lipophilic material concentrations and also by altering the product application dosing.

5. Conclusion

This project offers a three-prong methodological approach to developing and testing hair styling products for textured hair. In addition to practical goals as detangling, textured hair has its specific aesthetic and sensory characteristics which should be closely reflected in the testing methods. Developing a system for correlating the direction of the stress test results following different treatments with the product's texture and rheology can be used for screening and selection of active ingredients. The active Triolein is one of the many lipophilic actives considered, however simpler emulsions could be effective too, hence it is important to be clear about which goals are being met if more complex formulations are created. Exploring the rheological profile of the formulations in relation to tress testing also has the potential to generate a predictive product performance framework and thus benefits the development of more efficacious products for textured hair.

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