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The Effect Of Moisture And Finishing On Thermal Comfort And Selected Mechanical Properties Of Denims With A Portion Of Synthetic Fibres

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1. Subject matter and objective of work

This Study aims at the development of a model to predict thermal resistance of fabric under dynamic wet conditions and investigation of changes in thermal comfort and thermal parameters (conductivity, absorbtivity, resistance) of 180 denim samples made by using five types of weft, three sorts of weaves and 12 kinds of washing process under dry and wet conditions. It was found that thermal resistance model had a significant agreement with the experimental value and could be used for the prediction of thermal resistance of fabric made of different yarns under dynamic wet conditions. Various objective and subjective tests show that denim (functional denim) made by using spun polypropylene and cotton shows more resistance to drop of thermal resistance during wet conditions as compared to conventional denim and provides dry and warm feeling to user due to higher thermal absorbtivity. It has the highest moisture management capability. Besides that it provides higher moving comfort. Moreover, air permeability, bending rigidity, colour changes during industrial washing, subjective evaluation, coefficient of friction and geometrical roughness of denim samples were tested and a scattered picture was found. On the basis of analytical values, it can be said that functional denim made by using cotton and spun polypropylene is a product that can be used for better thermal comfort under highly wet and cold conditions. In addition use of polypropylene reduces the quantity of required fibre for same thickness of denim due to its low density. Polypropylene partially replaces cotton for the denim manufacturer. Moreover, functional denim needs less water for washing and less heat for drying. Above all, it does not provide favourable environment for the growth of bacteria while wearing.

2. Overview of current state issues

2.1 Thermal conductivity, moisture and temperature

Work of Elansaria and Hobanib [1] is an advantageous effort to identify the relation between changes in moisture, temperature and thermal conductivity. They proved that there is a positive and near linear relation between temperature and thermal conductivity. Nevertheless, they used some food items for their study but we can apply it in fabric. It shows that in fibre, that has less specific heat values, becomes hotter than the fibre that has higher specific heat values, ultimately would lose its thermal resistance, and consequently would lead to a stage where human being has to feel less relief.

2.2 Thermal conductivity of textile materials

Thermal conductivity of fabric is not thermal conductivity of polymers present in it. It is a combined effect of polymers and air. Fabric is a porous material and pores are filled with air. Moreover, there is a certain amount of moisture in it depending upon the humidity in environment. Crow [2] considers it as thermal conductance or thermal transmission rather than thermal conductivity. It can be understood from the Debye equation [3-5]:

$$\lambda = \sum_k C_k \upsilon_k l_k \qquad (1)$$

Where λ is the thermal conductivity, C_k v_k l_k is specific heat, phonon group velocity, phonon free path of mode k respectively.

2.3 Thermal conductivity and porosity of textile

Major heat transfer between two surfaces of fabric is through conduction and less than 5% is through convection and radiation [6]. Generally, it may be true but in case of porosity, it may not work, because porosity can increase the share of convection and radiation. Sugawara and Yoshizawa [7] conducted a comparison and found that porosity played a significant role in thermal conductivity. They added that size and shape of pores had a significant contribution in thermal conductivity of any porous material. Sugawara and Yoshizawa have developed the following equation to determine thermal conductivity of any porous material:

$$\lambda = (1 - A)\lambda_s + A\lambda_f \tag{2}$$

$$A = 2\frac{2^n}{2^{n-1}}\left(1 - \frac{1}{1 + P^n}\right) \tag{3}$$

Where, λ - overall thermal conductivity of the porous material, λ_s and λ_f –thermal conductivity of solid and fluid respectively, p is porosity, n is empirical component determined by mode of packing, pore size, pore shape and emissivity inside the pore n>0

2.4 Thermal absorbtivity

Warm-cool feeling of fabric is much important for the end users. People observe it during a short contact with fabric. Thermal absorbtivity b of fabrics was introduced in 1987 by Hes [3] to characterize thermal feeling (heat flow level) during short contact of human skin with the fabric surface.

$$b = \sqrt{\lambda \rho C} \tag{4}$$

Where ρc [Jm^{-3}] is thermal capacity of the fabric and the term b presents thermal absorbtivity [$Ws^{1/2}m^{-2}K^{-1}$] of fabrics. The higher is thermal absorbtivity of the fabric; the cooler is its feeling. In the textile materials, this parameter ranges from 20 for fine nonwoven webs to 600 [$Ws^{1/2}m^{-2}K^{-1}$] for heavy wet fabrics.

2.5 Porosity and water in fabric

For density computation Militky [8] proposes the following equation, which works better than simple geometrical porosity as given by Cay:

$$\varepsilon = \frac{\rho_w}{\rho_f} \tag{5}$$

$$\rho_d = 1 - \varepsilon \tag{6}$$

Where, P_d is porosity “density” with reference to density, ρ_w and ρ_f are the densities of fabric and fibre, ε represents the amount of fibre ratio in total system, W_p is planner weight of fabric [gm^{-2}], h is fabric thickness [mm]. For fabrics having more than one type of yarn, weighted average of different fibre density is taken.

2.6 Thermal conductivity of heterogeneous material

Sum of thermal conductivity of a heterogeneous material is not simple, particularly, in case when there is an interaction between diverse materials. For example, water in cotton fibre. In this case, there is a possible change in the structure of fibre.

The following equation can be used for summing of thermal conductivity of diverse materials:

$$\lambda_{ab} = b_r\lambda_a + (1-b_r)\lambda_b + Ib_r(1-b_r) \quad (7)$$

Where I is interaction between a and b and b indicates the ratio of a and b in the substance. Thus for the simplicity, Militky proposes the following equation to determine the sum of thermal conductivity of cotton and, polypropylene PET in denim under discussion [9].

$$\lambda_{ab} = b_r\lambda_a + (1-b_r)\lambda_b \quad (8)$$

Where, λ_{ab} is combined thermal conductivity, b_r represents the proportion of fibre a.

2.7 Moisture in wet fabric

In our case we need to know the amount of water and air and their location, in series or parallel. Surface area is more prone to evaporation as compared to inner area.
Following equation has been used to measure the proportional ratio of moisture in wet fabric:

$$\mu = \frac{F_w - F_d}{F_w} \quad (9)$$

Where, μ is water content in fabric, F_w is weight of wet fabric and F_d is weight of dry fabric without moisture. It is obvious from above equation that we have taken amount of moisture by considering the total weight of wet fabric as 1.

2.8 Moisture and density of fabric

There is significant impact of moisture in the structure of fabric, particularly made of hygroscopic fibres. Following equation can be used to predict the density of a cotton fibre under wet conditions. It is worth noting that density of cotton is 1540 Kgm^{-3}, whereas, density of water is 1000 Kgm^{-3}. In addition to that there is swelling phenomenon. Due to swelling, volume of cotton will increase and finally density will decrease.

$$\frac{1}{\rho_w} = \frac{\mu}{1000} + \frac{1-\mu}{\rho_d} \quad (10)$$

Where μ is moisture content.

2.9 Thermal resistance under wet condition

Thermal resistance is one of the crucial factors that contributes to better thermal comfort. It is imperative for design purposes of new fabrics and prediction of their thermal comfort. Fabrics are now and then used in wet state but research reports on experimentally determined thermal comfort properties of fabrics in the wet state are not many [10-13]. We could not find any study dealing with thermal resistance due to change in moisture percentage. The reason of this situation probably depends upon the fact, that common measuring instruments cannot measure thermal parameters of wet fabrics, due to long time of measurement, during which the fabrics get dry. The instrument used in this study was the commercial PC evaluated Alambeta thermal comfort tester, which provides reliable non-destructive measurement of thermal insulation and thermal contact properties of fabrics in the dry and wet state, thanks to very short time of measurement [12].

2.10 Moisture management in fabric

When water is dropped on the surface of any textile material, it moves in multi directions. Its movement depends upon the chemical and physical nature of the textile material. The ability to control the movement of moisture is called moisture management of textile material [13].

2.11 Friction coefficient and geometrical roughness

Sensorial comfort depends upon tactile properties of fabric. Broega et al. [14] have preferred coefficient of friction for the assessment of sensorial comfort.

2.12 Bending rigidity

Bending rigidity plays a significant role in mechanical comfort. It describes the stiffness of fabric during movement. It is one of the factors, which plays a significant role in the selection of clothing.

2.13 Impact of fibre composition and washing process on vapour permeability resistance of denim [m^2PaW^{-1}]

Vapour permeability of fabric helps to keep the skin dry under wet condition. Particularly in case of sweating, it plays a significant role. But at the same time, we need fabric, which should provide us shield from strong wind. Moreover, should not help in removing our body heat during winter times. Industry is using membranes to make fabric waterproof and at the same time improving its breathing capability.

2.14 Impact of industrial washing on colour

There is an understood change in colour after industrial wash with some chemicals. This change depends upon the type of chemicals being used and the type of fibres present in fabric. Spectrophotometer (Data Color Spectra Flash) using light source D65 and 10° CIE 1976 L*a*b* (CIELAB) equation is commonly used for this purpose.

2.15 Subjective evaluation

As concluded by Barker [10], objective and subjective measurements, both were incredible and are capable to serve certain purposes. Although, none of these is enough to predict the overall comfort, yet testing machine can tell thermal conductivity of any fabric, friction of the fabric surface and many more parameters.

2.16 Split-plot analysis

There is a strong dependence of thermal properties of fabric and the textile auxiliaries applied. Study of Tzanov et al. [15] provided enough evidence to establish this link. Amid et al. [16] have studied the impact of finishes on thermal properties and said in their concluding remarks that there was a significant link between the application of finishes and the thermal properties. To test the impact of fibre composition and application of finishes split-plot design was used. Split-plot design is a process in which main plot is considered hard to change and small scale experiments are conducted by dividing the whole plot into sub-plots [17].

3 Experimental part

Research design contains the following components:

1. Conventional and functional denim samples development
2. Denim sample testing
3. Data analysis

3.1 Denim sample development

Three types of weaves, five types of weft yarn and 12 types of industrial washing processes were used to develop 180 denim samples.

3.2 Testing parameters

Following areas were selected for testing and evaluation:

1. Thermal parameters
    a. Thermal conductivity
    b. Thermal absorbtivity
    c. Thermal resistance
2. Air permeability
3. Vapour permeability resistance
4. Colour changes due to washing
5. Moisture management
    a. Moisture absorption rate and time for front and reverse side of denim
    b. Wetted radius of front and reverse side of denim
    c. Front and reverse spreading speed
    d. Accumulated one way transport index
    e. Overall moisture management index (OMMC)
6. Kawabata Evaluation System for the testing of:
    a. Surface friction
    b. Geometrical roughness
7. Warp and Weft Bending Force
8. Subjective evaluation for the testing of:
    a. Warm and cool effect
    b. Softness
    c. Smoothness
    d. Stretch
    e. Bulkiness

f. Overall comfort

3.3 Testing equipment

Following testing instruments have been used for this study:

1. ALAMBETA testing equipment has been used to measure thermal parameters [12].
2. PERMETEST for vapour permeability resistance [18]
3. KES for testing of friction and geometrical roughness of denim
4. Moisture Management Tester (MMT) to test the response of denim when water is dropped on its surface.
5. UNIEG for bending force
6. Air Permeability Tester ATLAS
7. DATA COLOR

3.4 Subjective evaluation

A group of 30 educated people was selected for the subjective evaluation.

3.5 Testing conditions

All tests were carried out in lab where temperature was kept between 20-22 and RH 20-25%.

4. Evaluation of results

4.1 Thermal resistance prediction model for fabric under wet conditions

Fabric may be composed of one type of fibre or it is a combination of different fibres. In case fabric is composed of different fibres, average thermal conductivity can be calculated by using Equation 8. In the following equation, we have used ratio of polymers in the total volume of the fabric as discussed in section 2.6.

$$R_f = \frac{h\varepsilon}{\lambda_{wf}} \tag{11}$$

$$R_a = \frac{h(1-\varepsilon)}{\lambda_a \mu} \tag{12}$$

$$R_w = \frac{h(1-\varepsilon)}{\lambda_w \mu} \tag{13}$$

Where:

h [m] is average fabric thickness measured with the help of Alambeta, R_f, R_a R_w [m^2KW^{-1}] is thermal resistance of fibre, air and water, λ_w, λ_a [$m^{-1}K^{-1}W$] is thermal conductivity of water, and fibres present in the fabric λ_{wf}, is weighted average thermal conductivity of warp and weft, μ - proportion of moisture in fabric, ε-fibre volume ratio, 1-ε –porosity of the fabric.

We do not have any evidence about the arrangement and presence of fibre, moisture and air in the fabric. However, we can assume following possible configuration:

1. All resistances are parallel
2. All resistances are in series
3. Air and moisture in parallel and fibre in series

By applying above-mentioned approaches, we could get substantial agreement with the following arrangement:

$$R_{ts} = \frac{h\varepsilon}{\lambda_{wf}} + \frac{h(1-\varepsilon)}{\lambda_a \mu + \lambda_w \mu} \quad (14)$$

Where R_{ts} is total thermal resistance of the system. This model shows that thermal resistances of air and moisture are in parallel and then it is presumed in series with fibre. This equation is purely based on simulation. It is almost impossible to determine the share and location of water and air present in fabric. Moreover, there is a continuous process of evaporation.

Thermal resistance prediction model to determine thermal resistance under wet conditions is one of the most consequential outcomes of the whole study. This model has been developed considering that fabric is composed of yarn (warp and weft) of same or of more than one kind of fibre, moisture and air.

4.2 Functional denim characteristics

Second most significant outcome is the development and testing of functional denim. Functional denim made of cotton and Spun PP keeps its thermal resistance property in wet conditions better than conventional denims, even better than denim made by using cotton as warp and AT[1] PP, [2]SBC PP and PET[3] as weft. In addition, we found that higher porosity

[1] Air Textured Polypropylene,

[2] Stuffer Boxed Crimped Polypropylene

[3] Polyethylene terephthalate

means higher thermal resistance. It shows that replacement of air gaps with polymers will reduce the thermal resistance since polymers have lower thermal resistance than air.

4.3 Impact of weave on thermal parameter

Results authenticate that type of twill weave has no significant influence on thermal parameters (conductivity, resistance, absorbtivity) of denim.

4.4 Thermal parameter and application of auxiliaries

It was deduced that there is a significant adaptation in thermal parameters due to the presence of textile auxiliaries. It emerges that one should be attentive while selecting textile auxiliaries to keep thermal parameters under desired limits.

4.5 Thermal parameter under wet conditions

Denims made by Spun PP and AT PP as weft yarn exhibit greater consistencies under wet conditions as compared to denims made by using PET, cotton and SBC PP as weft yarn under wet conditions. Thermal resistance of denims made by using Spun PP and AT PP is 50% higher than other denim samples.

4.6 Moisture management comparison

Moisture Management Tester results fortify that Spun PP has the highest capacity to manage the moisture. Moister Management Tester (MTT) provides Moisture Management Capability (OMMC). This instrument authenticates that Spun PP can manage moisture and does not create a highly wet impression and keeps its dryness intact.

4.7 Coefficient of friction and geometrical roughness

KES was used to measure friction and geometrical roughness. It is visible from the results that coefficient of friction of filaments is lower than the staple. Air texture, SBC and PET have low values as compared to cotton and Spun PP. There is the same case with the geometrical roughness. Denim made by SBC PP possesses the lowest geometrical roughness, nevertheless, cotton is second to it and Spun PP follows.

4.8 Vapour permeability of functional and conventional denim

Vapour permeability of fabric helps to keep the skin dry under a wet condition, particularly in case of sweating it plays a critical role. Apparently, there is no set pattern in the response of different denims. We come upon a scattered picture, which registers that there are many factors, which are causing the vapour permeability. Nonetheless, denim made by cotton has lesser vapour permeability resistance

4.9 Airflow of conventional and functional denim

Airflow is one of the main characteristics of fabric. It plays a significant role in overall thermal comfort. Denim made by cotton and Spun PP has the highest airflow it is mainly due to the staple fibres used to make these yarns.

4.9 Bending rigidity of functional and conventional denim

Bending force represents the bending rigidity of any material. Results tell about the bending force of different denims. Spun PP has the lowest bending force, which means that it creates fewer hindrances in the movement of a body. Denim made by cotton and Spun PP has the highest airflow, it is mainly due to the staple fibres used to make these yarns.

4.11 Colour change pattern and industrial washing

It was observed that bleaching creates a drastic difference in colour changes. Nevertheless, there is no difference in functional and conventional denim behaviour.

4.12 Subjective evaluation

In general, people feel that Spun PP denim is softer and smooth. However, conventional denim is preferred in the area of overall comfort when it is compared with Spun PP denim.

4.13 Impact of different softeners on hand feel

Different softeners are applied for better hand feel. We applied two different softeners and subjective evaluation was conducted. Study finds that people prefer the hand feel of denim treated with silicone softener as compared to cationic softener.

5. Evaluation of results and new knowledge

1. Mathematical equation has been developed to predict thermal resistance of fabric under different wet condition. There is a need to work to find out the exact relationship between thermal conductivity and moisture in the fabric taking into account the interaction between water and cotton.
2. Spun PP gives much better results but denim made by it has a very uneven surface due to the presence of polypropylene outstanding fibres. These fibres cannot be removed by passing fabric through a singeing machine or by treating with enzymes. There is a need to develop technology to have a clean and shining surface like conventional denim so that it should fulfil the psychological comfort of the people.
3. AT PP filament is second to Spun PP. Denim made by AT PP does not create a big issue in surface look. It has no free ends and AT PP can replace Spun PP. Nevertheless, cotton loose ends can be removed by using strong enzymatic treatments.
4. In this study, a fix percentage of polypropylene was used. It is suggested that using different percentages of polypropylene and cotton should make a new kind of denim. It is hoped that most optimum combination could be determine.

6. Work related to the author studied the issue

6.1 Journal Publications (accepted and published)

1. Mangat, M.M., Militký, J., and Hes, L. , Thermal Resistance of Cotton Denim Fabric under various Moisture Conditions. Journal of Fibres and Textile, 2012(1): p. 36-47.
2. Magnet, M. M., Husain, T. and Bajzik, V.: Impact of Different Weft Materials and Washing Treatments on Moisture Management Characteristics of Denim. The Journal of Engineered Fibres and Fabrics, 2012, 7:1, p. 38-48

3. Bajzík, V., Mangat, M.M., and Hes, L. , Effect of two types of softeners and weft composition on thermal comfort characteristics of denim fabrics Journal of Fibres and Textile, 2011. 4: p. 3-8.
4. Abbasi, A.M.R., Mangat. M. M., Baheti, V. K., and Militky, J. Electrical and Thermal Properties of Polypyrrole Coated Cotton Fabric, Journal of Fibres and Textile. Accepted for publication
5. Mangat, M. M., Wiener, K. and Rehan, A.M.R., Evaluation of changes in colour of denim after various industrial washings with different fibre compositions, Journal of Fibres and Textile, Accepted for publication

6.2 Conference papers:

1. Hes, L. and Mangat, M. M.: Effect of industrial washing on thermal comfort. In: 7th International Textile Conference - TEXSCI 2010 Liberec, 2010.
2. Mangat, M. M., Bajzik, V. and Hes, L.: Influence of Cationic and Silicone Softeners and Weft Variation on Thermal and Sensorial Characteristics of Denim Subjective and Objective Evaluation. In: Proceedings of the COVITEX 2011, Pakistan 2011.
3. Mangat, M. M., Hussain, T., Hes, L. and Mangat, A. E.: Effect of Denim Clothing Finishing Processes on Physical Characteristics of Denim Fabric. In Proceedings of the AUTEX 2010, Lithuania 2010.
4. Mangat, M. M. and Hes, L.: Thermal parameters of Novel and Traditional Denim under wet condition. In: Proceedings of the Fiber Society Conference Hong Kong, May 23-25, 2011.
5. Mangat, M. M. and Hes, L.: Thermal parameters under wet conditions. In: Proceedings of the International Conference on Textile and Clothing, Lahore, March 28-29, 2011.

6.3 Journal Publications (under review)

1. Mangat, M.M., and Hes, L., Influence of Moisture Variation on Thermal Parameters of Conventional and Functional Denim. Journal of Engineered Fiber and Fabric.
2. Mangat, M.M., Havelka, A., and Fleglova, Z, Sensorial Comfort Appraisal of Denim by Objective Assessment of Surface Mechanical Characteristics. Under review Journal of Fibres and Textile

6.4 Under preparation

1. Mangat, M. M., Bajzik, V. and Hes, L.: Thermal properties of fleece fabric of different compositions under wet conditions
2. Mangat, M. M., Bajzik, V. and Hes, L.: Impact of compression on thermal properties of denim of different composition under wet conditions
3. Mangat, M. M., Bajzik, V. and Hes, L.: Impact of compression on thermal properties of fleece fabric of different composition under wet conditions
4. Mangat, M. M., Bajzik, V. and Hes, L.: Air permeability of fleece fabric of different composition under wet conditions

7. References

1. Elansaria, A.M., and Hobanib, A.I., *Effect of Temperature and Moisture Content on Thermal Conductivity of Four Types of Meat.* International Journal of Food Properties, 2009. **12: 2**: p. 308 - 315.
2. Crow, R.M., *Heat and moisture transfer in clothing systems. Transfer through materials, a literature review Part 1*1974, Ottawa: Ontario: Defence Research Establishment.
3. Van Krevelen D W, *Properties of Polymers, Correlations with Chemical Structure*1992: Elsevier.
4. Sakiadis, B.C., and Coates, J., *Prediction of specific heat of organic liquids.* AICHE JOURNAL, 1956. **2**(1): p. 88-93.
5. Krevelen, D.W., and Hoftyzer, P. J. , *Properties of Polymers, Correlations with Chemical Structure*1972 Elsevier.
6. Hollies, N.R., et al., *A Human Perception Analysis Approach to Clothing Comfort.* Textile Research Journal, 1979: p. 557-564.
7. Sugawara, A., and Yoshizawa, Y., *An Investigation on the Thermal Conductivity of Porous Materials and its Application to Porous Rock.* Journal: Australian Journal of Physics,, 1961. **14**: p. 469.
8. Militky, J., *Prediction of Textile Fabrics Thermal Conductivity*, in *Thermal Manikins and Modelling*, J. Fan, Editor 2006.
9. Militký, J., and Havrdová, M., *Porosity and air permeability of composite clean room textiles.* International Journal of Clothing Science and Technology, 2001. **13**(3/4): p. 280-289.
10. Barker, R.L., *Effects of Moisture on the Thermal Protective Performance of Firefighter Protective Clothing in Low-level Radiant Heat Exposures.* Textile Research Journal, 2006. **76**(1): p. 27-31.
11. Hes, L., *Thermal comfort properties of textile fabrics in wet state*, in *Proc. Izmir Internat. Textile and Apparel Symposium*2007: Cesme (Turkey).
12. Hes, L., *Thermal properties of nonwovens.* Congress Index 87Genf, 1987.
13. Hu, J., Hes, L., Li, Y., Yeung, K. W., Yao, B. , *Fabric Touch Tester: Integrated evaluation of thermal–mechanical sensory properties of polymeric materials.* Polymer Testing, 2006. **25**(1081): p. 1081-1090.
14. Broega, A.C., Nogueira, C., Cabeço-Silva, M. E., and Lima, M.,. *Sensory comfort evaluation of wool fabrics by objective assessment of surface mechanical properties* in *AUTEX 2010 World Textile Conference* 2010. Vilnius
15. Tzanov, T., Betcheva, R., and Hardalov, I. , *Thermophysiological comfort silicone softeners-treated woven textile materials.* International Journal of Clothing Science and Technology, 1999. **11**(4): p. 189-197.
16. Amid, H., Nosraty, H., and Maleki, V., . *Effects of Nano-Silver Finishing On the Physical and Mechanical Properties of Cotton Fabrics*. in *7th International Conference - TEXSCI 2010* 2010. Liberec, Czech Republic.
17. Jones, B., and Nachtsheim, C. J., *Split-Plot Designs:What, Why, and How.* Journal of Quality Technology, 2009. **41**(4): p. 340-361.
18. Hes, L., Araujo, M. D., *Simulation of the Effect of Air Gaps between the Skin and a Wet Fabric on Resulting Cooling Flow.* Textile Res. Journal, 2010. **80**(14): p. 488-1497.

8. Summary

First objective of this study was to develop a model for the prediction of thermal resistance of fabric made by using different types of fibres under wet condition. Second target was to manufacture of denim able to provide better thermal and sensorial comfort under wet condition. For this purpose, 180 denim samples were produced and more than 3000 different tests were carried on different equipments. Results show that thermal prediction model has a substantial agreement with actual values and denim made by using spun PP provides better thermal and sensorial comfort to wearers under dynamic wet conditions.

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