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Thermal Conductivity modeling and heat capacity evaluation of Porous Abrasive Agglomerates Based on Flash Method Measurements

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Abstract: This paper focused on studying the thermophysical properties, specific heat capacity and thermal conductivity, as well as improving the quality and proportions of chemical additives to the basic components such as abrasive granules of agglomerated aluminum oxide (Al_2O_3), water and dextrin compound. Measurements were carried out directly based on the detailed scanning technique of the main components of the laboratory-prepared samples (dry) - (38A60LVB5 - wet) - and this allowed for determining how the specific heat capacity (Cp) of these samples depends on the temperature within a specific range of 10 to 80 degrees Celsius. The results obtained from the model and mathematical equations related to the thermal properties showed that the thermal conductivity of the grinding wheels is low for the dry sample, unlike the wet sample, which has high conductivity relative to its moisture content. Therefore, it depends on the coolant used during the cutting process. The triangular microstructure model used to calculate the thermal conductivity of the experimental samples showed that the thermal conductivity depends on the apparent density of the two samples for both the dry ($X = 0$ kg/kg) and low-moisture ($X \approx 0.0065 - 0.01$ kg/kg) conditions.

Keywords: Specific heat capacity, Thermophysical properties, Thermal conductivity, Triangular microstructure model.

نمذجة التوصيل الحراري وتقييم السعة الحرارية النوعية لتكتلات المواد الكاشطة المسامية باستخدام طريقة الوميض

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المستخلص: ركزت هذه الورقة على دراسة الخصائص الفيزيائية الحرارية السعة الحرارية النوعية والموصلية الحرارية كذلك تحسين جودة ونسب المواد الكيميائية المضافة الى المكونات الاساسية كالحبيبات الكاشطة من أكسيد الألومنيوم المتكتل (Al_2O_3) والماء ومركب الدكسترين أجراء القياسات بشكل مباشر بالاعتماد على تقنية المسح التفصيلي للمكونات الرئيسية للعينات المحضرة معمليا (الجافة - 38A60LVB5) - (الرطبة -38A60LVB5)وقد سمح ذلك بتحديد كيفية اعتماد السعة الحرارية النوعية (Cp) لهذه العينات على درجة الحرارة ضمن نطاق محدد يتراوح بين 10 الى 80 درجة مئوية. أظهرت النتائج المتحصل عليها من خلال النموذج والمعادلات الرياضية المتعلقة بالخصائص الحرارية ان الموصلية الحرارية لعجلات التجليخ منخفضة للعينة الجافة على عكس العينة الرطبة عالية التوصيل نسبة لمحتوى الرطوبة وبالتالي تعتمد على سائل التبريد اثناء عملية القطع. اظهر نموذج البنية المجهرية المثلثية المستخدم في حساب الموصلية الحرارية للعينات التجريبية اعتماد الموصلية الحرارية على الكثافة الضاهرية للعينتين لحالتي الجفاف ($X = 0$ كجم/كجم) والرطوبة المنخفضة ($X \approx 0.0065 - 0.01$ كجم/كجم)

الكلمات المفتاحية: السعة الحرارية النوعية، الخصائص الفيزيائية الحرارية، الموصلية الحرارية، نموذج البنية المجهرية المثلثية.

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1. Introduction

The thermal capacity and conductivity are not only the central knowledge to the optimization of the drying process in which cracking and structural defects are tendencies that are usually known to start but also in the optimization of the performance of vitrified grinding wheels in long-term operations. Drying is a very delicate process because moisture gradients bring about internal stress that can result in circumferential or radial or axial cracks. Adequate thermophysical data enable the prediction modeling to ensure that energy consumption is minimized and also the product quality is not compromised [1,6,7].

Density, specific heat capacity, thermal diffusivity, and thermal conductivity are the thermophysical properties of the heat and mass transfer. Density affects the thermal conduction and movement of moisture in the porous structure directly. Changes in the binding, grain packing and compaction have an impact on the look of the density and porosity and hence alter the level of conduction of the heat. Specific heat capacity, an additive measure of binder, abrasive grains and moisture content, is a thermal energy storage measure that is determined by use of a differentiating scan calorimetry system MDSC 2920 [2,3]. Thermal diffusivity defines the rate of heat propagation in the material and it was determined through the flash method and is linked to the conductivity by the following governing relationship:

$$\boldsymbol{\lambda = \alpha \cdot \rho \cdot Cp} \qquad (1)$$

where thermal conductivity, thermal diffusivity, specific heat capacity and density of the material are represented by lambda, alpha, rho, and Cp respectively. To measure thermal conductivity, experimentally measured parameters are then modeled empirically i.e., series-parallel model, triangular models to explain the influence of porosity and moisture [6-10].

Material composition has a great influence on these thermophysical responses.

Although the use of vitrified bonded grinding wheels has become extensively industrialized, the phase of their production involving drying is still the bottleneck of the process and in which high temperatures, water movement and other internal forces often create structural defects. One of the closely related phenomena is cracking (its appearance can be circumferential, radial or axial) which is directly associated with poor knowledge of the heat and mass transfer in porous abrasive agglomerates.

Current production procedures are usually based on the empirical drying schedules, which do not entirely involve a precise thermophysical property information, constraining the forecast of defect development as well as energy use [1].

One of the key issues is how to measure *thermal diffusivity* and *thermal conductivity* of green abrasive material in two situations: dry and wet conditions. Those are intrinsically sensitive to the microstructure, the composition of binders, the porosity distribution, and the amount of water in it, all of which vary in a dynamic manner and affect the thermal behavior. Although one can determine the density or heat capacity separately, integrated modelling methods that relate experimental values of flash-method diffusivity with effective thermal conductivity predictions are not well-developed in porous abrasive systems [2,3,4,10].

Lack of credible thermophysical data limits the formulation of holistic heat and mass transfer models that can be used to simulate high fidelity drying kinetics. This means that manufacturers are exposed to high chances of product rejection, high levels of energy consumption, and poor-quality assurance. In addition, the changes in heat capacity and thermal conductivity motivated by moisture make the interpretation of drying dynamics challenging, and it is necessary to experimentally verify modeling frameworks that can represent the coupled thermal characteristics of heterogeneous agglomerates of abrasives.

3. Materials and Methods of Measurements

3.1. Composition of Abrasive Grinding Wheels

The bonded abrasives are often referred to as the grinding wheels but they are usually manufactured as bored cylinders although some other types of cylindrical forms are also there, which are determined by the application. The grinding wheel is a cutting tool in the form of a rotary instrument that removes micro-chips of material off the surface of mechanical parts in the machining process [1]. The main two constituents of a grinding wheel include; calibrated abrasive grains which remove the material and a binder that binds the agglomerate and keeps the wheel in one piece [1].

- Bonded abrasives refer to two types of abrasive depending on the variety of abrasives: Al_2O_3
- The material is corundum (corundum) and silicon carbide (SiC).
- Super abrasives: Cubic boron nitride (CBN) and diamond which are more expensive and harder.
- The traditional abrasives are also distinguished based on the binder

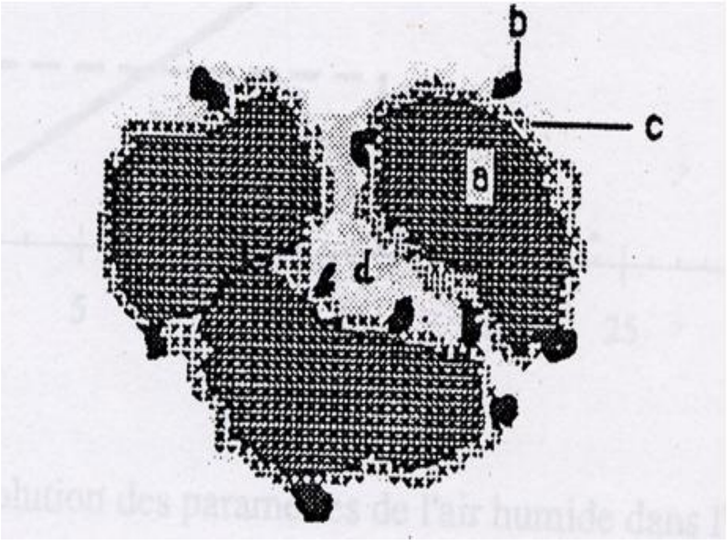

Figure 1: Schematic visualization of the internal structure of the green grinding wheel: a – abrasive grains, b – vitrifiable binder, c – primary binder, d – pores

Figure 1 shows the microstructure of the unfired (green) abrasive agglomerate which contains three components: abrasive alumina grains and vitrifiable binder and primary binder and air-filled pores.

2.2. Composition of Abrasive Grinding Wheels of 38A120LVB5

2.2.1. Alumina Grain Size Effect

Al_2O_3 of two grain sizes and the literature data [7,8] respectively. The observed minor deviations of the experimental values are ascribed to surface oxidation, impurities and slight differences in the crystalline structure of samples. Small-grain alumina has a tendency to have slightly higher specific heat because of the surface area and defect density which allows higher storing of energy at a microscopic level. This fact highlights the relevance of using grain size in the modeling of thermal behavior in grinding wheel materials.

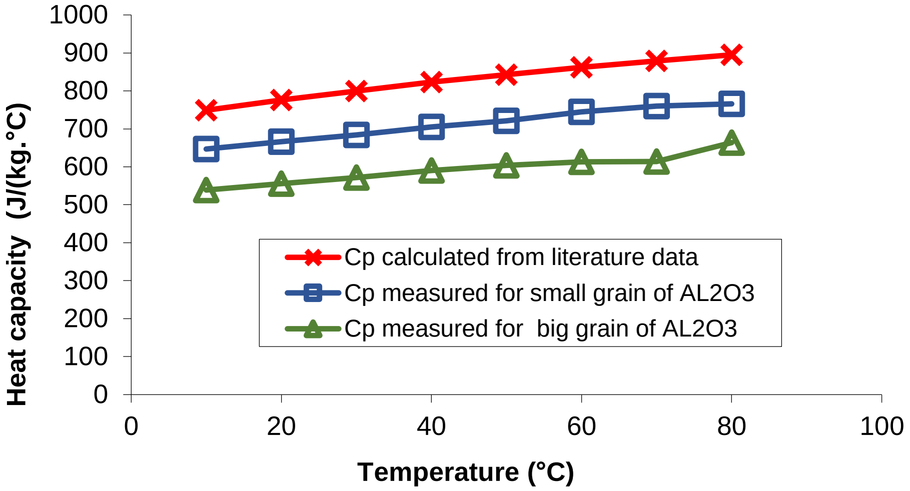

***Figure 2**: Experimental and literature thermal capacity of Al_2O_3 for two grain sizes*

Figure 2 shows the comparison of the specific heat capacity of alumina that was experimentally determined.

2.2.2. Specific Heat of Constituents 38A120LVB5

Figure 3 shows the experimental specific heat capacity development with temperature of 38A120LVB5 formulation that includes alumina, vitrifiable binder B5US, dextrin and calcium lignosulfonate. The incorporation of lignosulfonate, a hydrophilic organic binder, alters the thermal response of the earlier formulations, especially in the intermediate temperatures where water desorption adds to the absorption of energy. The low- to mid-temperature region is dominated by the specific heat of the binder fraction, whereas the high-temperature behavior is regulated by the grains of alumina [1,2,6].

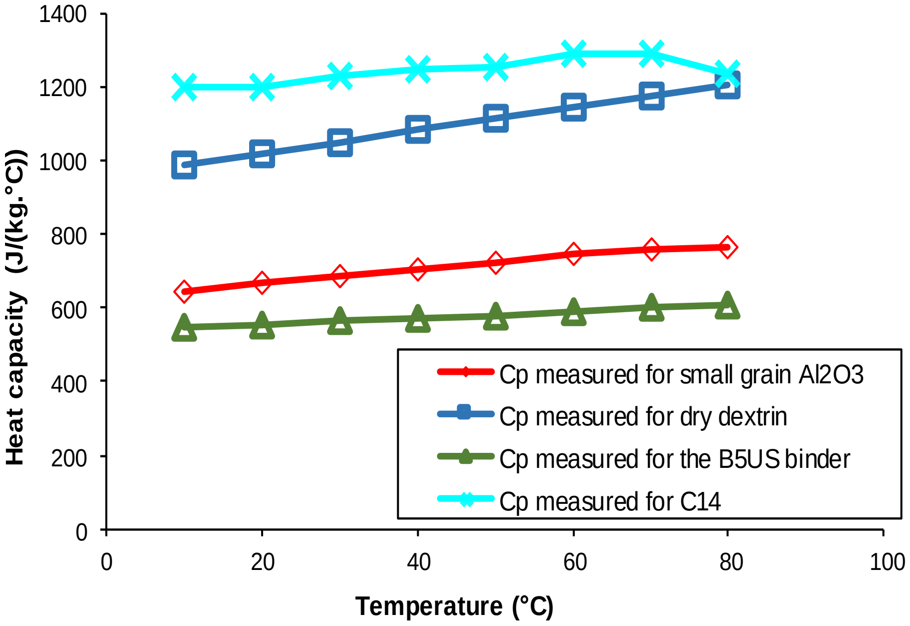

Figure 3: Experimental specific heats of constituents vs. temperature for 38A120LVB5

Specific heat capacity development against temperature of constituents of 38A120LVB5 specification (alumina, vitrifiable binder B5US, dextrin, calcium lignosulfonate). These experiments prove that the thermophysical signature of each formulation is different and the modeling requires individualized characterization. This type of data can be used in creating numerical models of heat and mass transfer to optimize the drying cycle of various grinding wheel compositions at minimal energy use and without thermal damage [1,3,5,6,9].

4. Mathematical Equations for the thermal properties and the applied model

The following equation was used to compute the apparent density: $$\rho = \frac{m}{V} \qquad (2)$$

m = mass in (kg), V = volume in (m^3) where: ρ = apparent density in (kg/m^3),

For controlling equations of heat transfer, the following differential and non-differential equations serve as the foundation for the mathematical modeling of thermal characteristics.

The following equations were used to compute thermal conductivity

$$dQ/dt = -\lambda .\, S\, (\vec{n} \;.\; gra\vec{d}\;T) \qquad (3)$$

where: dQ/dt is the heat flux, in Watts, S is the cross-sectional area and $grad\ T$ is the temperature gradient within the material, in °C/m

$$\left(\frac{\partial T}{\partial x}\vec{x}+\frac{\partial T}{\partial y}\vec{y}+\frac{\partial T}{\partial z}\vec{z}\right) \qquad (4)\; gra\vec{d}T =$$

λ is the thermal conductivity of the material assumed to be isotropic and is expressed in W/(m.K).

Thermal diffusivity is defined from Fourier's second law (heat equation), which describes the penetration of heat (transient regime) through a material subjected to any thermal perturbation, namely

$$(5)\,\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$

Where T is the temperature at a point with coordinates (x, y, z) and a, the thermal diffusivity expressed in m2/s and assumed to be constant (independent of position, time and temperature).

4. Results and discussion

4.2 Microstructural Triangular Model calculation for Thermal Conductivity.

The model **microstructural Triangular** used in calculating the thermal conductivity of the experimental samples is illustrated in the figure below. The heat flow in this model is modeled using a triangular resistance network that is a solid bridge between solid bridges and binder.

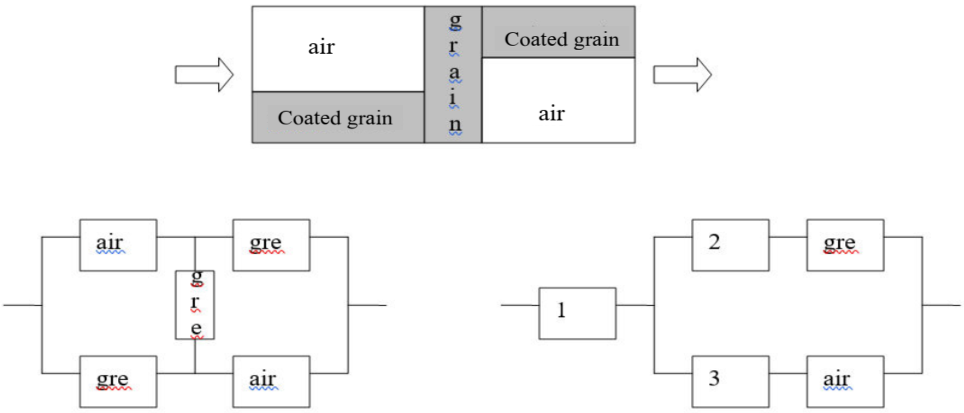

Figure 4: Schematic of triangular arrangement

The triangular shape also considers other heat transfer directions that are available as a result of solid connectivity and offers a more accurate approximation of the effective conductivity [6,10]. Figure 6 depicts a triangular bridging model as a triangular resistance network between solid heat flow paths.

4.3 Fitting of a Model and Experimental Results. Coated

The experimentally obtained data points of thermal conductivity versus apparent density of the dry and wet samples are shown in Figure 5. The fitted curves of the triangular model is superimposed.

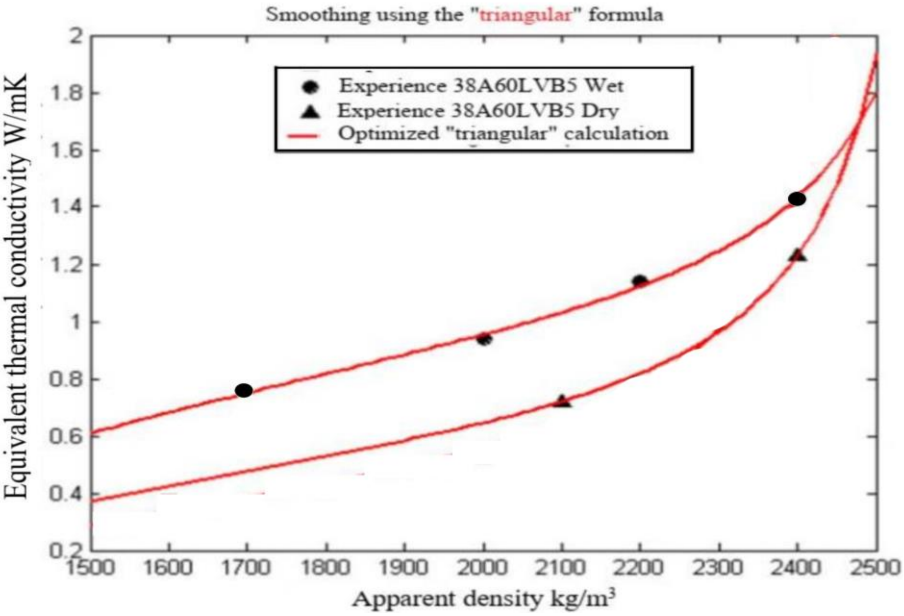

Figure* 5: *Thermal conductivity vs. apparent density for 38A60VB5 wet and 38A60VB5 dry specifications (experimental and model predictions)

The findings indicate that the conductivity is proportional to the density as air fraction is less and there is better contact between the solid and solid whereas moisture content decreases thermal conductivity slightly because, water-filled pores have lower conductivity than the solid body [1,2,6].

5. Discussion

5.1 Specific Heat Capacity (Cp): Effects on Temperature and Composition.

This was evidenced by the experimental results which showed that Cp rises as temperature rises with all constituents and composite formulations, as is observed with ceramic and organic materials as higher degrees of freedom of vibration are encountered with high temperatures. Moreover, grain size and binder composition also had a strong effect on Cp values: formulae with smaller grain fractions of alumina showed a small difference in heat capacity at low temperatures whereas hydrophilic organic binders (e.g., lignosulfonate) increased effective Cp in intermediate temperature regions than silicones because of the effect of desorption and water [13].

5.2 Experimental Methods: Flash and Reliability of Measurement.

The precision of thermal diffusivity measurement determines the validity of λ determination. The laboratory flash method was adopted in this study based on the same basic principle as such tests as the international ISO 18755:2022 and ISO 19629:2018 that are describing flash thermal diffusivity testing on ceramics [11]. Although such ISO protocols are targeted at monolithic and composite ceramics with controlled geometries, the flash method is the gold standard because of its speed, a small sample preparation, and an extensive applicability.

Recent studies in methodology in laser flash measurements indicate that current work focuses on improving test parameters (e.g., thickness, pulse width) and data analysis algorithms so as to achieve maximum accuracy, especially in heterogeneous or porous samples [15]. These enhancements confirm the relevance of the flash-based diffusivity findings and emphasize the importance of a cautious experiment design an aspect that the present study authors undoubtedly take into consideration. The literature has acknowledged one such limitation, which is that highly porous material could become less useful in measuring the diffusivity in typical flash configurations because of light transmission and surface irregularities; modifications such as opaque foils or pulse parameter optimization can reduce such errors [15]. Although the present research does not specify such alterations, the fact that the measured trends in the study have been consistent with the known behavior of porous materials indicates that experimental uncertainties did not undermine validity of the findings in the research.

5.3 Drying Modeling and Drying Industrial Processing Implications.

One of the main driving forces of this study is to offer thermophysical information that could be used to augment predictive models in the coupled heat and mass transfer process in drying of green grinding wheels. Proper modeling of drying kinetics needs to have reliable input parameters on Cp 0, 0 and 0 at different contents of moisture and temperature. The current results particularly the λ relationships depending on density and the effects of moisture are physiologically reasonable and provide a robust empirical foundation to computational heat transfer models.

6. Conclusion

Regarding the specific heat capacity, measurements performed on all major components of the lumpy material confirmed good agreement with the simple additive equation weighted by mass fractions. Since the thermal diffusivity of the lumpy abrasive is easier to measure using the flash method than the plate method (with porosity control, a small cylindrical disc can easily be produced from a large rectangular plate), the thermal conductivity was derived from the diffusivity.

References

1. PECZALSKI, Roman. Hygrothermal and mechanical behavior of hydroscopic abrasive agglomerate. Application to the drying of grinding wheels. Thesis: Claude Bernard University – LYON 1 1994.

2. GONNET Elisabeth. Determination of the thermal diffusivity of food products by the impulse method. Application to pasta products. Thesis: Claude Bernard University – LYON 1 1987.

3. BEN ABDELOUAHAB, J. Development and automation of a calorimeter for measuring the heat capacity of foodstuffs. Thesis: Sci.: National Institute of Applied Sciences of Lyon, 1994. 153p.

4. DICKERSON, R.W. An apparatus for Measurement of thermal diffusivity of foods. Food technol., 1965, Vol. 19, N° 5, p. 198-204

5. PARKER, W.J., JENKINS, R.J., BUTLER, C.P. and ABBOTT, G.L. Flash method of determining thermal diffusivity, heat capacity and thermal conductivity. J. of Applied phys., 1961, Vol. 32, N° 9 ,p.1679- 1684.

6. HEATING ENGINEER'S REFERENCE GUIDE, coordinator F. MASSARD, Elsevier, Paris 1997

7. Wang, C.; Zhang, F.; Pan, J.; Mao, J.; Long, Y.; Huang, H.; Wang, C.; Lin, H.; Deng, X.; Wu, S. An experimental study on preparation of vitrified bond diamond grinding wheel with hollow spherical corundum granules as pore former. *Int. J. Adv. Manuf. Technol.* **2017**, *93*, 595–603.

8. ROBERT, C. Weast, Ph.D. HAND BOOK of CHEMISTRY and PHYSICS EDITION 1986- 1987.

9. DEGIOVANNI A. 6 1977. Diffusivity and flash method. Rev. Gen. Thermal. Fr., 185, 420-441.

10. CHEMICAL NEWS MARCH 1999, PP 13-20.