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Temperature-dependent specific heat capacity for dry and wet vitrified-bond grinding wheels: Models of experiment and prediction

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Abstract:
The vitrified-bond grinding wheels find a lot of application in the precision grinding where it has gained fame due to its versatility and high performance. These wheels are made of a mixture of small grains of abrasive polishes like aluminum and carbide with a bonding material (aluminum or ceramic), which offers the same strength and stability. Applications of them include a large variety of industries: metalworking and tool production, aerospace, lighting, as well as automotive, where they may offer efficient material removal and office finishes. The natural durability and bristle stability of the glass-bonded grinding wheels guarantee the high quality of the outcome in application to differing grinding applications, specific heat capacity (Cp) of the vitrified-bond grinding wheels plays a vital role in defining the capacity of a grinding wheel in the absorption and storage of the heat generated during the grinding process without overheating. Having a high (Cp) is useful in alleviating thermal shock, avoiding thermal damage to the workpiece (burning), and enhancing the efficiency and life of the wheel in terms of cooling control and a balanced distribution of the heat. Typically, a high (Cp) will help in improved temperature control during the grinding process particularly in processes where high accuracy is in demand and also in processes that demand large volumes of material removal.

The paper aims at establishing the specific heat capacity (Cp) of vitrified-bond grinding wheels with agglomerated aluminum oxide abrasive grains in a given temperature range of 10-80 o C. A modified differential calorimeter (MDSC 2920) was used to carry out experiments of samples 38A120LVS and 38A60LVB5 because it could determine the temperature dependence of the specific heat capacity. In this temperature range, Cp rose in line with temperature. Another predictive model, $Cp\cdot = \Sigma \; xi \; Cpi \; (T)$was constructed using the mass ratios and demonstrated the best agreement (average deviation = 5% or higher). These were the dry (X = 0 kg/kg) and the low wet (X ≈ 0.0065 -0.01 kg/kg) conditions. These data were used in the correct modeling of the drying processes so as to reduce crack defects in the glass wheels due to thermal stress.

Keywords: Specific heat capacity, thermophysical properties, vitrified abrasives, temperature dependence, additive prediction model, DSC measurement, grinding wheel drying.

السعة الحرارية النوعية المعتمدة على درجة الحرارة لعجلات التجليخ ذات الرابطة الزجاجية الجافة والرطبة: نماذج تجريبية وتنبؤية

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الملخص

تعتبر عجلات التجليخ الكاشطة ذات الرابطة الزجاجية أدوات أساسية في عمليات التجليخ الدقيقة، وتشتهر بتعدد استخداماتها وأدائها العالي. تتكون هذه العجلات من مزيج من حبيبات كاشطة مطحونة بدقة، مثل أكسيد الألومنيوم أو كربيد السيليكون، ورابطة زجاجية أو خزفية، مما يمنحها قوة وثباتًا استثنائيين. تستخدم هذه العجلات على نطاق واسع في صناعات متنوعة، من تشغيل المعادن وتصنيع الأدوات إلى صناعات الطيران والفضاء والسيارات، حيث تُوفر إزالة فعّالة للمواد وتشطيبات سطحية فائقة. إن المتانة المتأصلة والثبات الحراري لعجلات التجليخ ذات الرابطة الزجاجية يجعلها أدوات أساسية لتحقيق نتائج عالية الجودة في مجموعة متنوعة من تطبيقات التجليخ، تعد السعة الحرارية النوعية *(Cp)* لعجلات التجليخ ذات الرابطة الزجاجية حاسمة في تحديد قدرة العجلة على امتصاص وتخزين الحرارة الناتجة أثناء التجليخ دون ارتفاع مفرط في درجة حرارتها كذلك تساعد *(Cp)* العالية في تقليل الصدمات الحرارية، منع التلف الحراري للشغلة (الحرق)، وتحسين كفاءة وعمر العجلة من خلال إدارة التبريد وتوزيع الحرارة بشكل أفضل. بشكل عام، تساهم *(Cp)* في تحسين التحكم في درجة حرارة عملية التجليخ، خاصة في التطبيقات التي تتطلب دقة عالية وإزالة كميات كبيرة من المواد.

تهتم هذه الورقة بتحديد السعة الحرارية النوعية *(Cp)* لعجلات التجليخ ذات الرابطة الزجاجية المحتوية على حبيبات كاشطة متكتلة من أكسيد الألومنيوم ضمن نطاق دراسة محدد لتغير درجات الحرارة والواقع بين 80 - 120 درجة مئوية. أجريت التجارب على العينات (38A120LVS و 38A60LVB5)باستخدام المسعر التفاضلي المعدل (MDSC 2920) وهذا سمح بتحديد اعتماد درجة حرارة السعة الحرارية النوعية على درجة الحرارة. ضمن هذا النطاق ازدادت (Cp) خطياً بتغير درجة الحرارة. تم تطوير نموذج تنبؤي إضافي $Cp\cdot = \Sigma\ xi\ Cpi\ (T)$ بناء على النسب الكتلية، وأظهرت اتفاقاً ممتازاً (انحراف متوسط بنسبة $\geq$ 5%). شملت النتائج الحالة الجافة ($X = 0$ كجم/كجم) والرطوبة المنخفضة ($X \approx 0.0065$ - 0.01كجم/كجم). وفرت هذه البيانات أساساً لنمذجة دقيقة لعمليات التجفيف لتقليل عيوب التشققات في العجلات الزجاجية الناتجة عن الاجهاد الحراري

الكلمات المفتاحية: السعة الحرارية النوعية، الخصائص الفيزيائية الحرارية، المواد الكاشطة المزججة، الاعتماد على درجة الحرارة، قياس، DSCتجفيف عجلة التجليخ، نموذج التنبؤ بالمواد المضافة.

1. Introduction

Within the framework of the modelling process of the drying of grinding wheels, manufacturers would like to study the thermal properties of the vitrifiable bond-based grinding wheels in the green (unfired) form. This research paper is a pre-study to establish the coupled heat and mass transfer during the drying stage that is significant to correct quality of the products, as well as prevent structural failures. Previous research has also suggested that hygrothermal behaviour can only be described successfully to develop valid drying models and optimization of the process [1,6]. In most industrial sectors, there are the uses of bonded abrasives in the form of grinding wheels (sharpening, grinding, and cutting wheels). These tools are typically composed of aluminium oxide, zirconium oxide or silicon carbide that is bonded collectively either by using a vitrified bond or with a phenolic resin. As a result of such differences in the needs of industries, grinding wheels of different types are manufactured as depicted in Figure 1.

The discussion in this paper is about the vitrified-bond grinding wheels having fine grains of aluminium oxide with a characteristic dimension of approximately 200percentimeters and cylindrical geometries of various dimensions. The other typical application of these types of abrasives is in grinding crankshaft journals where the most significant factor is dimensional accuracy and thermal stability [1,7].

Figure 1. Grinding wheels- Aluminium oxide - Vitrified - glass-like bond - Voids or porosity

The traditional principles of the ceramic-processing are used to prepare vitrified grinding wheels. Production process incorporates four significant steps. During the mixing stage, the abrasive grains are coated by primary binders and a vitrifiable bond, to create a moist sand-like powder. By pressing the powder in a mold, the required density of the bulk is attained until an annular shape of the grinding wheel is achieved. Pressing of the green wheel followed by blowing of hot air in the oven to kill the moisture. Finally, post-firing at high temperatures provides the product with the final mechanical stability, besides, microstructural stability [1].

The research is anchored on the past research on hygroscopic agglomerates of abrasives, and the main objective of the research is through experimental determination of the thermal properties (specific heat capacity of dry and slightly wet) at the green state. Models of predictive modelling, numeric simulation of drying kinetics and temperature distribution within the grinding wheel would require thermal property data with respect to reproduction [1,6]. The experiment has been limited to the two mixtures of bonded abrasives. The analysis of the thermo-characteristics of the selected material follows the description of the selected material and comparison of thermal characteristics of the dry and moist sample as a variable of the sample properties (density and moisture content). The methods that can be thermally characterized on the same materials include calorimetric methods and transient thermal analysis which are valid in the determination of thermal capacity and diffusivity [2,3,4].

In the fabrication of vitrified bonded grinding wheels, the green (unfired) agglomerate of abrasive is taken through a significant drying temperature after which it is heated at a high temperature (up to approximately 1280 °C) in vitrification. Industrial experience also indicates that about 5 percent of the grinding wheels produced contain structural defects; also, that a certain proportion (40-45) of the defects are in the form of reproducible crack patterns that may contain circumferential, radial or axial cracks. The revelations point to the fact that the drying process has to be regulated to ensure the quality and structural integrity of products [1].

The main explanation of these cracks is the lack of uniformity of moisture removal and the resultant thermo-hydro-mechanical stresses that are developed during drying. The moisture gradients and internal stresses by thermal gradients generate differential shrinkage in the porous agglomerate. In addition, the capillary forces provided by the liquid with the aid of the pore system may be stronger than the mechanical strength of the green material which leads to the crack formation and consequently the crack propagation process. Previous studies of hygroscopic abrasive agglomerates have shown; behaviour of drying is extremely sensitive to both the phenomena of coupled heat and mass transfer, as well as to the thermophysical properties of material [1,6].

These phenomena should be well understood in order to make adequate prediction and control of the processes involved in coupled heat and mass transfer. However, there are still few valid temperature-dependent thermophysical properties such as specific heat capacity Cp(T) dry and wet of typical industrial vitrified abrasive formulas such as the 38A series bonded by FA443 and B5US vitrified binders. The imprecision of the numerical models that are used to model temperature fields and moisture migration in porous ceramic-like materials is limited by this absence of such data [1,7].

The absence of accurate Cp(T) The reality that (T) values are a major barrier to the development of powerful numerical models that can be employed to simulate drying kinetics, stress evolution, and the development of defects is an issue. The fundamental parameters in the mathematical model of heat transfer include the thermal properties specifically the specific heat capacity and the thermal diffusivity whose establishment is paramount in the simulation of the drying process within the industries to guarantee the reliability of the simulation. Examples of experimental methods that have been widely used in the characterization of such properties in heterogeneous porous materials are calorimetry and transient thermal methods [2,3,5,8].

The lack of plausible thermophysical information renders the optimization of the drying conditions i.e. temperature profiles, air velocity and humidity extremely empirical in nature and therefore, the existing production losses and lack of uniformity in the quality of products. It is reported that correct data on thermophysical properties is necessary in the prediction of thermal modelling and optimization of processes of the ceramic type materials and porous solids as per engineering sources [6,7].

The present research makes this gap by experimentally determining and studying one of the most significant thermal characteristics, that is, heat capacity, and its explicit dependence on temperature of dry and slightly wet vitrified bonded abrasive agglomerates as well as verifying a straightforward physically-based predictive model by the additiveness of constituent properties. The obtained results will be used as input parameters needed in terms of hydrothermal-mechanical modelling of vitrified grinding wheel drying process in the future and help to optimize the industrial drying processes [1,6,10].

1. Material and Methods

2.1. Material

The substance under analysis is an abrasive agglomerate, a porous substance that is employed in ceramic bonded grinding wheels. It consists of special additives (mixing process), calibrated abrasive grains which constitute the active portions of the tool, a primary binder which holds the molded shape together between the pressing and firing processes, and a vitrifiable binder which vitrifies during firing, making it to have the necessary mechanical strength. It should be subjected to intensive quality control tests as one last step in the manufacturing process.

In this work, two samples were made and Table 1 illustrates the entire chemical composition of both 38A120LVS and 38A60LVB5 abrasive specifications which includes their major building materials along with their weight percentages. The two grades hold pure alumina that exists in either fine or big grains to form the necessary abrasive functions which constitute about 87.7% of the total weight.

As to the ingredients of the first sample, 38A120LVS the vitrifiable binder (FA443) has approximately 12.2 percent which is used to sustain the product cohesion and its structural strength. The material has three small constituents that are dry dextrin and citric acid and liquid water that are present in an extremely tiny quantity and all these three constituents influence the binding efficiency and processing behavior. The knowledge of mass fractions is necessary in the material performance evaluation since it can be used to derive relationships between material compositions and performance outcomes in addition to being able to use regression models to predict thermal and mechanical characteristics. Specifications 38A120LVS and 38A60LVB5 have the following specifications as stated in the following tabular form.

Table 1. The precise compositions of specifications 38A120LVS and 38A60LVB5

38A120LVS	*Pure alumina (fine grain)*	*Vitrifiable binder (FA443)*	*Dry dextrin*	*Citric acid*	*Liquid water*
Mass fraction	*0.877*	*0.122*	*0.00096*	*0.003*	*0.00924*
38A60LVB5	*Pure alumina (coarse grain)*	*Vitrifiable binder (B5US)*	*Dry dextrin*	*calcium lignosulfate*	*Liquid water*
Mass fraction	*0.882*	*0.117*	*0.0080*	*0.0080*	*0.00924*

In the case of the second sample 38A60LVB5 abrasive specification, the primary constituents and their mass fractions of the same are tabulated above. It is made of an alumina that is fine-grain, about 88.2 percent that serves as the active abrasive material. Vitrifiable binder (B5US) also has a contribution of approximately 11.7% in structural integrity and binding strength. The existence of dry dextrins and calcium lignosulfate and liquid water that are in very minute amounts influences the binder performance and processing properties of the material. The full data of mass fraction makes it possible to develop predictive regression models that correlate material composition and mechanical and thermal properties.

2.2. Vitrified Bond Preparation

Each product (between 15 and 20 mg) was put into an aluminium DSC capsule, and a second empty capsule was used as a reference. The studied samples were in bulk powder form, room temperature (25 o C) conditioned and variable relative humidity. A liquid nitrogen cryotherapy unit (LNCA, TA Instruments) was placed on an MDSC 2920 device (Thermal Analysis Company, New Castle, Delaware, USA). Specification 38A120LVS then 38A60LVB5 components were experimented with. The 38A120LVS and 38A60LVB5 contain the same constituents with the same mass fraction of the constituent grains but vary in the grain size (mesh size). In calculating the heat capacity, the 38A60LVB5 sample was cooled at a rate of 5.00 o C/min until the temperature dropped to -20.00 º C and the 38A120LVS were heated at a rate of 5.00 o C/min till heating was completed to 100.00 º C.

2.3. Instrumentation and Calibration

2.3.1. Measurement and calculation of Specific heat capacity

The measurement of specific heat capacity was carried out using a Differential Scanning Calorimeter (DSC) as shown in Figure 2 designed to determine the heat flow associated with controlled temperature variations. The calorimeter system included a heating component and a thermally conductive measurement unit and thermocouples which detected temperature and a data acquisition system.

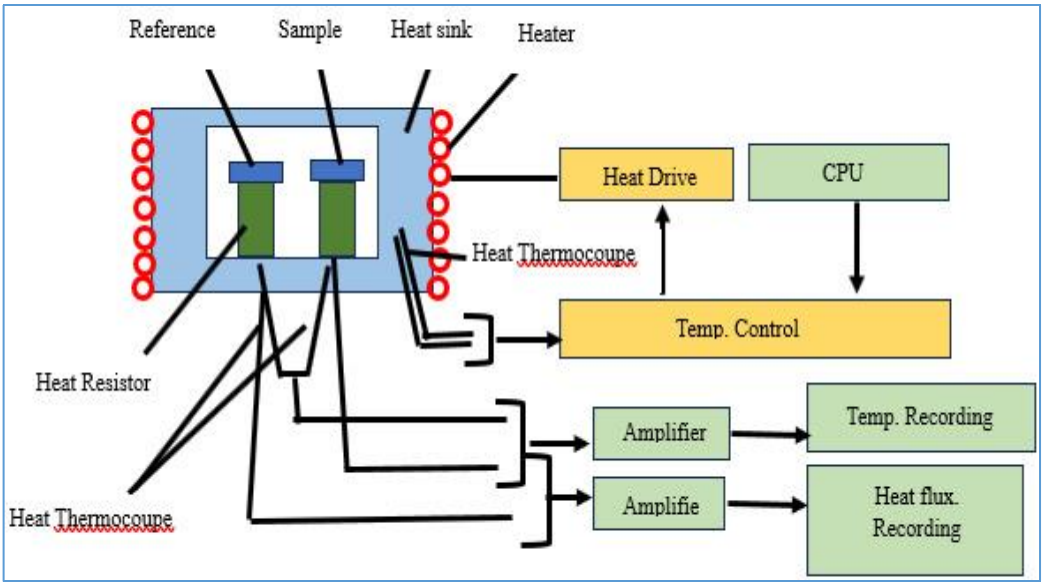

Figure 2. The main internal components of the scanning differential calorimeter (DSC).

The instrument worked on a programmed linear heating rate that allowed the constant recording of heat flow as a temperature-dependent function. The experiment controlled the thermal conditions that minimized uncertainties in the course of the measurement process [3,5].

To make the calorimeter system accurate and reproducible, the calorimeter system was calibrated before the experiments. The reference materials involved in the calibration process had known thermal properties to eliminate systematic errors in measurements of heat flow and temperature in both measurements. The calibration step involved checking of the temperature scale and calibration of the calorimetric sensitivity.

These measures provided a sure method of determining the temperature-dependent specific heat capacity of the vitrified bonded abrasive samples [2,3,6]. The calibrated instrument made it possible to measure both dry and moist samples at the entire temperature range with the right degree of accuracy. The data that were collected were subsequently incorporated into making predictive models that modelled heat transfer processes during the drying of the grinding wheel [1, 6].

The figure 2 gives the diagram of the calorimeter and explains how the instrument works to measure the specific heat capacity of the vitrified abrasive materials. It incorporates a sample holder and a reference cell that the design is arranged in symmetrical manner on a thermal conduction block that has a thermocouple. Heating system establishes an ideal heating environment which allows the accurate determination of the heat flow passing through the sample material. The thermocouples are the one that measures the temperature difference at two points which generate an electrical signal which indicates the amount of heat the material has taken in. The system secures heat loss through thermal insulation as well as ensuring the correct results of measurements.

The relation between temperature and time [T = f (t)] was measured and the temperature was assumed to be homogeneous in the block of copper, batteries, and sample. The signal recovered at the battery terminals was expressed by the relationship in equation (1):

$$U = S\left(\frac{\partial T}{\partial t} m_{sam}.C_{P,sam} + \frac{\partial T}{\partial t} X\right) \qquad (1)$$

Where X is the parameter of dissymmetry between the right stack and the left stack. Parameters U and X will be calibrated to obtain their values.

The device can be used in thermal analysis of vitrified bonded grinding wheel materials because the specific heat capacity will be measured with temperature variation in controlled heating tests.

Measurement of each component of bonded abrasive 38A120LVS and 38A60LVB5 was done 3 or 4 times respectively, dry and wet, as is given in the above procedure. The experiments give the temperature dependency of Cp 10 80 ° C. The experimental curves were averaged and the result smoothed using straight lines to obtain each component. When we measured the experimental heat capacities of the components (dextrin, citric acid), we have found that the heat capacity developed uncontrollably because of uncontrolled residual water content. We thus settled on conditioning our samples by subjecting them to an oven at 120 ºC over 2 weeks to fully dehydrate them.

In a second step, we consulted the literature data in the (Handbook of Chemistry and Physics [7]) to obtain correlation (2) for alumina:

$$C_{p_{Al2O3}} = \left(26.12 + \left(4.39.10^{-3}\right)\times T - \frac{7.27.10^{5}}{T^{2}}\right)\frac{4183}{102} \qquad (2)$$

With in (J/(kg.°C)), and T in K.

The temperature rise curve obtained allows calculation of the material's thermal diffusivity using analytical models which typically use Parker's theory as a base [13,15].

2.3.2. Mass heat correlation

The most common formula for making this estimate relies on the additivity of the specific heat capacities of the constituents:

$$Cp = \sum_i x_i * Cp_i \qquad (3)$$

Where represents the mass fraction of constituent (i), (0< x_i< 1), Cp_i : the specific heat capacity of each constituent (i) (J/kg°C). The experimental curves for each constituent are used to calculate the ΔH of the mixture. According to the additivity formula, all the experimental results were calculated using the formula below:

$$c_p^{agglo} = \sum_i x_i c_{pi} \qquad (4)$$

2.3.3. Apparent density

The abrasive agglomerate is a porous material, comprised of a solid material (grain + binders) and air. Its structure is assigned, depending upon the application to the industry, the name unit weight in the wet form and symbolizes the mass of the compound per unit of total volume (solid substance + air) occupied. It is generally referred to as bulk density.

The porosity of such a system is determined by the real density which is the mass of the material divided by the unit volume of the matrix. The density is normally determined depending on the nature of the product.

In the case of liquids, by densimetry (buoyancy method, a ballast diver is used, with a graduated rod) or by pycnometer (working with a known volume and precision).

In the solids, by the Archimedes pressure on the product, by equilibrium in a density gradient, by differential pycnometer, as immersed in a liquid. In the case of a porous solid the apparent density is given by the equation:

$$\rho_t = \rho_v \, (1 - \varepsilon_0) \qquad (5)$$

Where ε_0 designate the porosity of the porous solid and the actual density of the solid matrix. The apparent density, true density, and porosity of industrially manufactured material vary little within a grinding wheel. However, for reasons related to the study of the influence of structure, three ranges of apparent density and porosity will be examined in this work. Since the true density is fixed for a given composition, the corresponding values are recorded in the table below.

Table 2. Bulk density according to the composition.

Composition	ρ (True) [kg.m^{-3}] at 23 °C	Precision [kg.m^{-3}]
38A120LVS	3550	50
38A60LB5	3590	50

2.3.4. Thermal diffusivity measurement

Thermal diffusivity is defined from the second law of FOURIER (heat equation), which describes the penetration of heat (transient regime), through a material subjected to any thermal disturbance. On the other hand, this magnitude is related to the other thermophysical properties by the following classical relation:

$$\alpha = \frac{\lambda}{\rho_{app} . C_p} \qquad (6)$$

The flash diffusion technique is a useful means of establishing thermal diffusion properties of materials, including thin, solid samples. All that is needed is a brief powerful pulse of energy emitted by a laser or flash lamp onto a small disk-shaped specimen with temperature measurements of the opposite side of the specimen being made over varying time intervals.

The experimental setup is illustrated in Figure 3 that indicates the entry of the energy pulse by the front face of the specimen and the flow of the pulse by the rear surface where the sensor detects the change in temperature. The method provides rapid measurements values since it requires minimal sample work and can be utilized in the testing of numerous hard materials that contain metals and ceramics and polymers. The Flash Method is an effective method of thermal diffusivity measurement that is popular due to the fact that it offers precise data to be used in regression analysis [5,8,9].

The calorimetric and hygrothermal testing experiments provide valuable data regarding the behaviours of materials during varying environmental conditions and this is used to enhance the accuracy of statistical models prediction [1,3,6,7,10,12]. Regression applied to these datasets can help the researcher find the relationship between variables and examine the influence of various materials on the findings and formulate equations to explain the best parameter of materials and processing techniques.

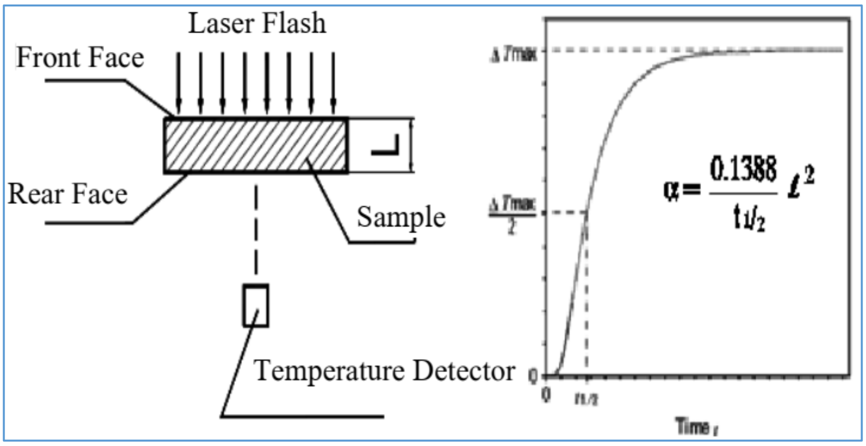

Figure 3. Laser flash method for thermal diffusivity measurement.

The diagram in Figure 4 displays a theoretical thermogram which shows how a material's temperature changes over time after it receives a brief energy pulse according to the Flash Method.

The curve typically exhibits a rapid rise in temperature of the sample at the rear of the surface and rises to the peak thereafter and starts to decline as the material becomes exposed to heat. The thermogram analysis allows the researcher to establish thermal characteristics that comprise of diffusivity and conductivity and heat capacity by measuring the time required to reach certain temperatures that denote the specific fraction of the maximum temperature change [2,5,8]. The theoretical thermogram provides a standard against which researchers make a comparison of the measurement accuracy and analyze the impact of various components of materials and their percentage compositions on thermal characteristics.

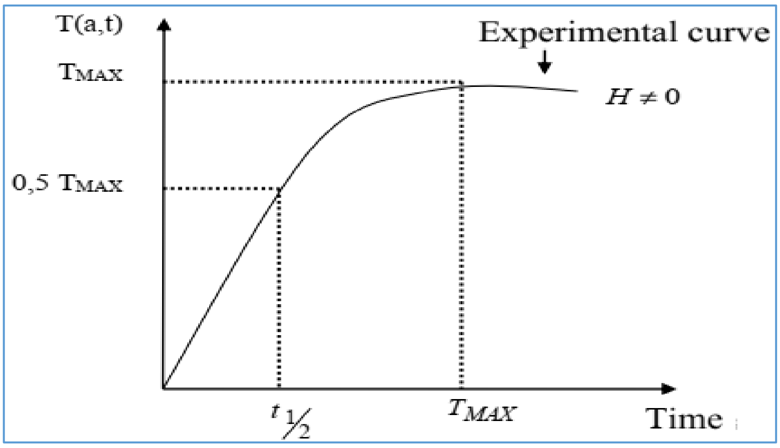

Figure 4. Example of a Theoretical Thermogram.

3. Results and discussion

3.1. Specific heat capacity

The additive model enables the optimal evaluation of thermal properties of composite materials by taking into account its simple structure which yields a full evaluation of the thermal characteristics in composite materials by evaluating all the parts of composite materials and employing their respective mass ratio [2,3,5,8]. The technique allows rapid evaluation of thermal behaviour, where no specific testing is necessary, so that it is useful in preliminary design work and in choice of materials. Additive model has successfully been tested using various materials which include foods and ceramics and abrasive composites and gave results that were comparable to experimental data of Flash Method and other calorimetric tests [2,4,5,8,9]. The additive model involved computing thermal properties by using true abrasive material compositions to provide a reference point to the research and predictive models in the form of regression models [3,5,6,10].

3.1.1. Dry state validation

Dry State Validation requires testing material thermal and mechanical characteristics in dry conditions which prevent any effect from moisture or volatile substances. Tables 3 compiles all the linear interpolation equations for the constituents of *38A120LVS*. Since dextrin is a highly hygroscopic component, measurement errors have likely affected the results. However, given its very low mass fraction in the abrasive agglomerate composition, these errors are likely negligible.

Table 3. Relationship between heat capacity and temperature as a function of the constituent.

38A120LVS	**Mass fraction**	**linear interpolation equations of Cp between T = [10-80] J/ (kg.°C)**	**Δ $\overline{Cp}$ J/ (kg. °C)**	**$\overline{Cp}$ J/ (kg. °C)**
alumina (big grain)	0,877	2,0 T + 542	10	626
Vitrifiable binder (FA443)	0,122	2,4 T + 893	62	1036
Dry dextrin	0,00096	3,1 T + 957	149	1098
Citric acid	0,003	2,6 T + 847	4	965
Liquid water	0,00924	Littérature	-	4188

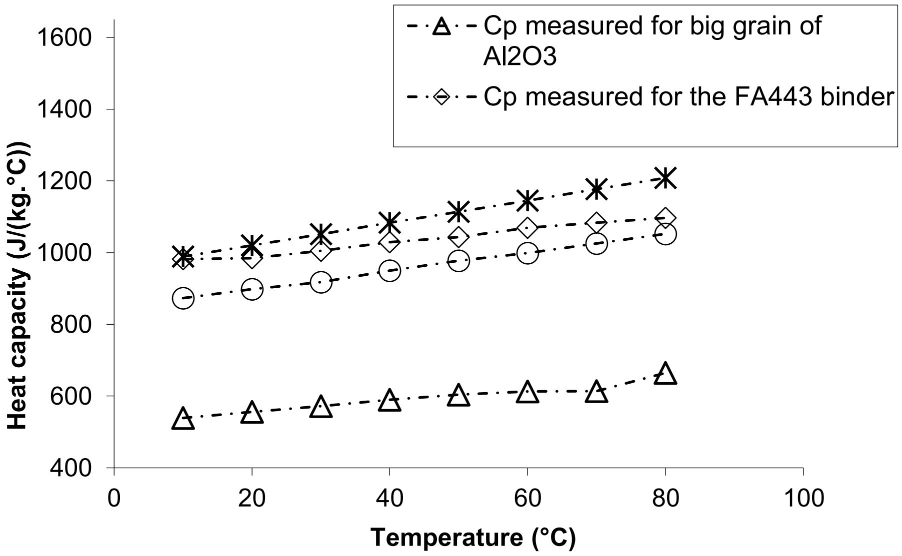

Figure 5. Experimental specific heats against temperature for 38A120LVS constituents.

This step is critical to ensure that the predicted properties, obtained from models such as the additive method or regression analysis, accurately reflect the intrinsic behaviour of the solid constituents [2,3,5]. The comparison of calculated values with experimental measurements on oven-dried or moisture-free samples enables researchers to identify discrepancies that occur due to water content or binder hydration, which helps them determine the actual thermal diffusivity and heat capacity Figure 5 for dry A38120LVS and structural characteristics of the material [4,5,8]. The validation process strengthens confidence in the predictive models while establishing a reference point for future studies that will examine hydrated or operational conditions [3,6,10].

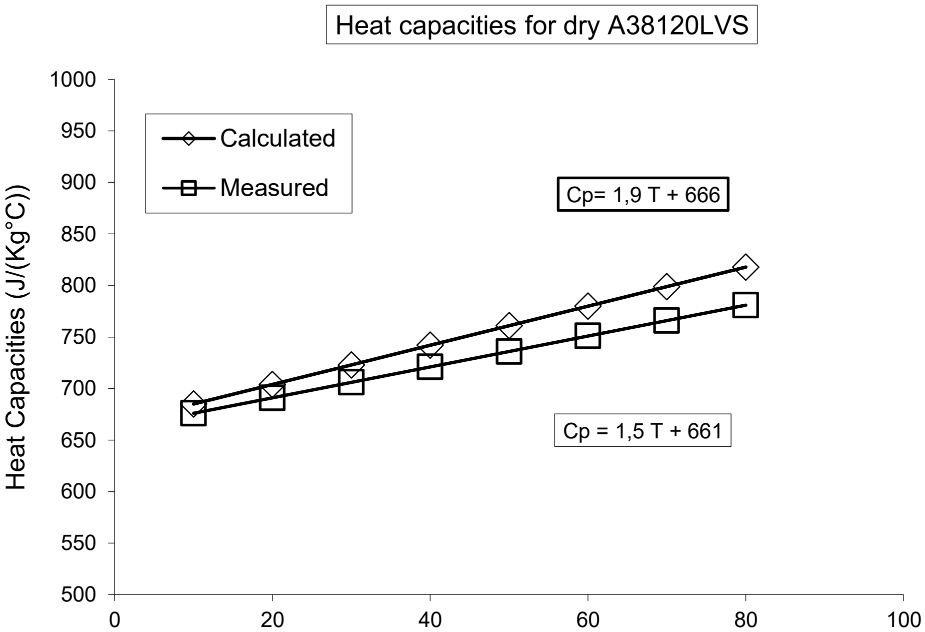

Figure 6. Calculated and measured heat capacities for dry 38A120LVS agglomerate.

The term Meaning of model codes denotes the definition and meaning of the symbols and notations used in a mathematical or physical model. The model requires complete specification of all variables, parameters, and coefficients because this information enables users to comprehend the model and reproduce its results as well as to implement it correctly. Figure 6 explains this part of the results typically includes the designation of thermal properties typically heat capacity against temperature, mass fractions of constituents, geometric parameters, and any empirical coefficients used in calculations. The model achieves complete understanding through its precise explanation of each notation because this process eliminates uncertainty about which specific terms will be used in the future evaluation and testing of results.

3.1.2. Wet state validation

The process of wet state validation tests how materials react to temperature changes and mechanical stress when they are exposed to wet conditions because moisture affects their thermal and structural properties. The presence of water or other liquids in wet conditions changes the heat transfer properties from dry conditions which requires scientists to validate their findings through experimental tests.

The evaluation of wet conditions requires researchers to measure actual properties and compare them against model predictions which use the additive model or regression-based estimates to determine hydration effects and moisture-related property changes [2,3,5,8,11]. Figure 7 illustrates the evolution of specific heat with temperature within the specified study range for the wet sample.

The process tests whether predictive models function accurately under actual operating conditions while it also delivers essential information for situations where materials experience high humidity or direct water contact [3,4,6,10]. Figure.8. shows calculated and measured heat capacities for wet *38A60LVB5* agglomerate. Tables 4 compiles all the linear interpolation equations for the constituents of *38A60LVB5*.

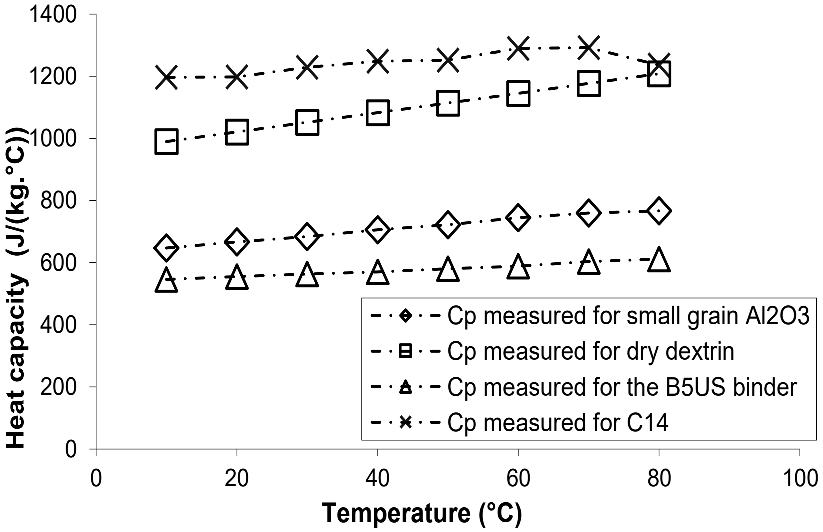

Figure 7. Calculated and measured heat capacities for dry 38A60LVB5 agglomerate.

Table 4. Linear relationships linking heat capacity to temperature as a function of the constituent.

38A60LVB5	Mass fraction	linear interpolation equations of Cp between T = [10-80] J/ (kg.°C)	Δ $\overline{Cp}$ J/ (kg. °C)	$\overline{Cp}$ J/ (kg. °C)
alumina (fine grain)	0,882	1,8 T + 631	52	711
Vitrifiable binder (B5US)	0,117	0,9 T + 534		578
Dry dextrin	0,00805	3,1 T + 957	149	1098
calcium lignosulfate	0,00805	1,5 T + 1831	39	1251
Liquid water	0,00924	Littérature	-	4188

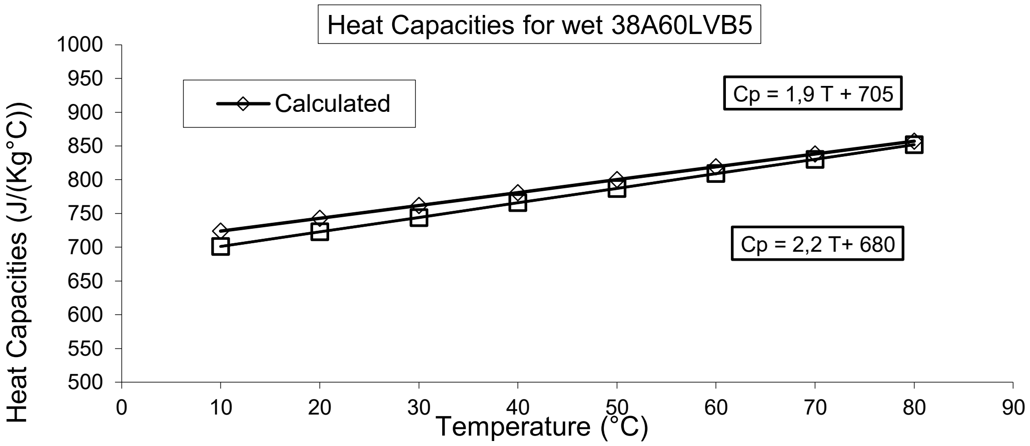

Figure.8. Calculated and measured heat capacities for wet (38A60LVB5) agglomerate.

3.2. Thermal diffusivity

The results show that thermal diffusivity increases with the apparent density of dry and wet agglomerates. The results obtained for each specification are shown in Table 10 below and in Figures 9 and 10.

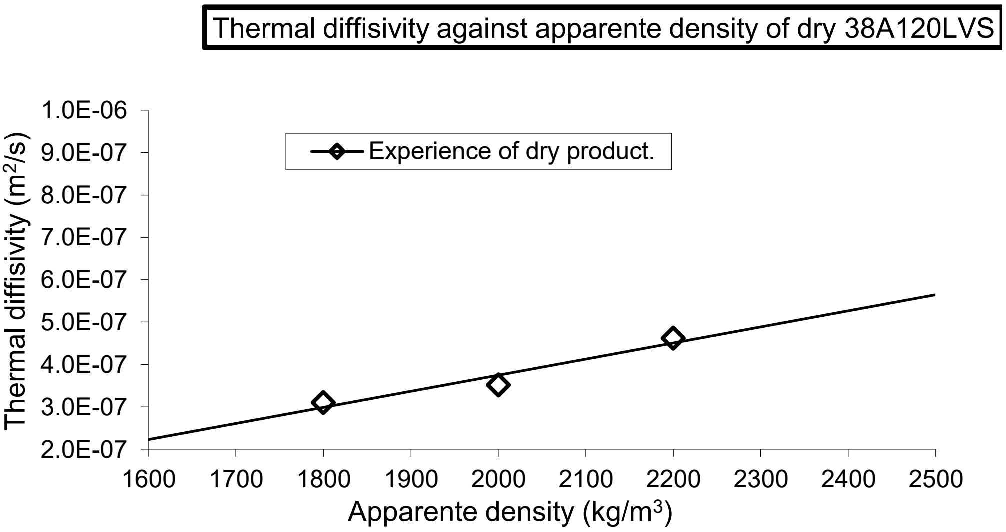

Figure.9. Thermal diffusivity measured for dry agglomerate (38A120LVS).

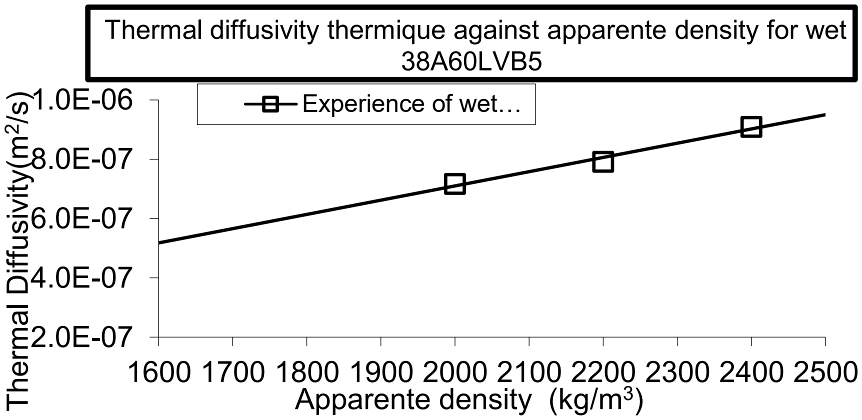

Figure.10. Thermal diffusivity measured for wet agglomerate (38A60LVB5).

3.3. Composition and Regression Summary

The Composition and Regression Summary gives a short summary that indicates that material composition influences thermal and mechanical property via a statistical regression analysis. The section shows the influence of various material compositions on thermal diffusivity heat capacity and structural behaviour by its overview of key component mass fractions and the regression model outcomes [1–5,8]. The summary assists users to locate their most significant features whereas it allows users to develop predictive models and compare results of simulation and actual tests in dry and wet conditions [2,3,5,6,10]. The combined approach allows the researchers to design materials effectively since it links material composition data with their real performance outcomes.

There were several experiments that were done on two samples at dry and moist conditions. The wet sample was dried at 200 ° C and the dry sample was humidified at a particular temperature of -25 ° C. The moisture content of the sample was calculated and experiments to show how the values of thermal diffusion changed prior to and after drying were done and the accuracy of the thermal data was established. Table 5 below and Figures above 7 and 8 represent the obtained results of each specification.

Table 5. Measured Thermal diffusivity (α) Results.

38A120LVS	Dry sample X=0 (g/kg), T=65°C	ρ (kg/m³)	1600	1800	2000	2200
		C*P* (J/kg.K)	-	744	744	744
		α (m²/s)	-	3.1E-7	3.52E-7	4.62E-7
	Wet sample X=6.5 (g/kg), T=25C	C*P* (J/kg.K)	779	779	779	779
		α (m²/s)	3,1E-7	3,1E-7	3,1E-7	3,1E-7
38A60LVB5	Dry sample X=0 (g/kg), T=65°C	ρ (kg/m³)	2000	2100	2200	2400
		C*P* (J/kg. K)	-	620	-	620
		α (m²/s)	5,56E-7	-	-	8,28E-7
	Wet sample X=6.5 (g/kg), T=25C	C*P* (J/kg. K)	656	-	656	656
		α (m²/s)	7.17E-7	-	7.91E-7	9.09E-7

The table above displays two abrasive materials *38A120LVS* and *38A60LVB5* which were tested under four conditions of various moisture levels and temperature conditions to determine their thermal properties. The key parameters which were measured in dry and wet conditions include density (ρ, kg/m^3) specific heat capacity (C_P, J/kg·K) and thermal diffusivity (α, m^2/s). The water content (X) and temperature (T) changes of each material show how moisture and thermal conditions affect the material's ability to transfer heat. The measurements establish critical information which supports validation of predictive models through additive model and regression analysis tests while showing how different compositions and environmental factors influence thermal performance. The results show that moisture content increases thermal diffusivity because it creates better heat transfer mechanisms while material properties lead to different reactions in specific heat and density under different conditions.

Table 6. Relationship between thermal diffusivity (α) and apparent density of (38A120LV & 38A120LVB5).

Sample condition	*Thermal diffusivity (*m^2/s)
38A120LVS dry	$\alpha = 4E -10 (\rho) - 4E-07$
38A60LVB5 wet	$\alpha = 5E -10 (\rho) - 3E-07$

Table 6 summarizes the measured thermal diffusivity (α, m^2/s) of the 38A120LVS and 38A60LVB5 abrasive materials as a function of its apparent density (ρ, kg/m^3) under dry and wet conditions. The thermal diffusivity in dry samples ranges between 4×10^{-10} and 4×10^{-7} m^2/s while wet samples show a decrease to thermal diffusivity values between 3×10^{-10} and 1×10^{-7} m^2/s which demonstrates how moisture reduces heat transfer efficiency. The data shows that thermal properties depend on bulk density and environmental conditions which scientists use to verify predictive models while studying how material structure and moisture levels affect thermal performance.

The measurement uncertainty of diffusivity can be estimated at $\pm0.3 \times 10^{-7}$ m^2/s. The differences in experimental values between dry and wet 38A120LVS agglomerate are therefore well below the experimental error, and it is thus not possible to differentiate between them. As for 38A60LVB5 agglomerate, it is more conductive in its wet state, as water significantly increases the conductivity of the binders that form the bridges between the grains. The increase in diffusivity with density is due to the decrease in volume.

4. Discussion

Vitrified bonded agglomerates of abrasive have a specific heat capacity (Cp) with temperature dependence that has a definite linear inclination within the temperature range measured at 10-80 o C. This linearity can be seen in accordance with the fundamental physics of the heat capacity of crystalline and amorphous solids at moderate temperatures. The temperature dependence of Cp of the crystalline forms such as alpha-Al2O3 (the most widespread form of material used as abrasive grains) is primarily attributed to the phonon mode excitation (lattice vibrations). The temperature rises make the number of phonon states at thermal accessibility increase slowly to the classical Dulong Petit limit, and the heat capacity rises slowly to the same thermal accessibility limit [7]. The same linear tendency is due to the amorphous or semi-crystalline components (vitrifiable binder FA443 or B5US, dextrin, citric acid and lignosulfonate) that not only depend on the configurational degrees of freedom, but also in the case of organic additives on vibrational and rotational excitations [6].

The additive model $Cp(T) = -x_i\, Cp_i(T) -x_i\, Cp_i(T)$, where xi is the mass fraction of component i and $Cp_i(T)$ is its measured linear fit has excellent predictive power (mean deviation < 5%). This high accuracy in turn implies that the agglomerate is macroscopically homogeneous and the phases do not interact chemically, or do not have an interfacial thermal impedance that would otherwise render them not to obey a simple a la masse additivity. This is the same behaviour of other multi-phase porous ceramics and composites with the volume fractions being well mixed and with low thermal boundary resistance [1,6]. The large positive change in the effective Cp can also be observed with the low moisture content (X 0065 (101) = 0.006501 kg/kg) which is evident in the wet-state validation (Fig.8). Water also contains a very large specific heat capacity (i.e., about 4188 J/kg 0 K) compared to the solid matrix (i.e., such as 6501100 J/kg 0 K) and its existence in the pore (or adsorbed on hydrophilic surface dextrin, lignosulfonate) is another heat reservoir. This effect is quantitatively determined in the additive model by adding water as a constituent when its known Cp value is added which demonstrates the strength of the method even in the presence of some water.

Implication to a process engineer Process engineering Process engineering is the direct consequence of such results, which have a direct effect on the modelling of drying green vitrified grinding wheels. The drying step is controlled by the combined mass transport and heat in which the accurate knowledge of *Cp(T)* is essential in the establishment of the amount of energy required to warm the material, generation of temperature gradient and rate of moisture loss [1]. The numerical modelling of energy balance is easy since the linear form of *Cp(T)* is in use, and the additive method has been shown to provide a crude estimate of *Cp* of new compositions by merely adjusting mass fractions and binder composition.

Another cause of the observed drying behaviour is the moisture-enhanced effect on the effective heat capacity (increase in Cp): an increase of effective heat capacity in wet areas is reducing the temperature increase rate and extent of thermal gradient, but increases the energy necessary to evaporate. It is the most crucial trade-off in the optimization of the drying schedules of precluding crack sing as a result of either excessive differential shrinkage, or excessive vapor pressure build-up [1]. The existing information can hence provide a viable thermophysical foundation to a future hygro-thermo-mechanism model to minimize the defect and maximize energy generation. In total, the linear dependence of temperature, the success of additive model, and measurement of the effect of moisture are all in line with the established theory and past studies of porous ceramics and composites. These results not only coincide with the rudimentary behaviour of heat capacity, but this can be directly translated into the process improvement in industry [1,6,7].

5. Conclusion

Specific heat capacity at constant pressure *(Cp)* values of dry and wet vitrified bonded abrasive at different temperature values of (10 to 80) °C were experimentally determined according to modulated differential scanning calorimetry. Measurement was done on the main constituents (alumina grains, vitrifiable binders FA443 and B5US, dextrin, citric acid, lignosulfonate and two typical industrial formulations) (*38A120LVS and 38A60LVB5*).

All the materials exhibited a strong linear temperature dependence of Cp, and no phase-lumps or strong non-linearities of the studied regime were observed. The temperature coefficient (dCp/dT) value was positive and rather constant, as expected with both crystalline and amorphous vibrational mode excitation.

A simple additive predictive model was developed: $Cp_{agg}(T) = \Sigma\ xi \cdot Cpi(T)$

xi is the mass fraction and *Cpi (T)* is the linear regression line of each constituent. This model was directly tested against measurements of agglomeration directly in both dry ($X = 0\ kg/kg$) and low-moisture wet-condition (X=0.0065-0.01kg/kg) resulting in excellent agreement (average deviation less than 5 percent over the entire temperature range). The effectiveness of the additive method proves the ability of the material to be regarded as the macroscopically homogeneous composite with no significant deviations of the mass-weighted behaviour because of the interfacial effects or chemical interactions.

It was discovered that the effect of moisture on effective *Cp* was strong with a significant shift to the upward direction even at low contents. The large specific heat capacity of water and distribution in the pore spaces and hydrophilic surfaces is quantitatively explained. The additive model best characterizes this contribution in the case when water is one of the constituent ingredients.

The *Cp (T)* data obtained and the approved predictive model are some of the essential input parameters in the numerical model of the drying process of the green vitrified grinding wheels. The precise information about the particular heat capacity is literally required to ascertain energy balances, field of temperature and the rate of evaporation of moisture that directly depends on the degree of drying induced stresses and the likelihood of cracking.

These results, therefore, explain the development of the optimal drying schedules that minimize the defect, and minimize the usage energy and losses of production. The simplicity and robustness of the additive model also guarantee that it is a convenient tool that can be used to evaluate the new abrasive formulations fast without having to institute prolonged experimental campaigns.

In conclusion, the provided work provides valid experimental findings and a proven modelling procedure of the thermophysical description of vitrified agglomerates of abrasives. These results are applied in improving the process knowledge and management in the manufacturing of the high-performance grinding wheels.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.