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Thermal Properties of Building Materials - Review and Database

by

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1. Foreword

The aim of this technical report is to present and give an overview of a dataset collecting the main thermo-physical properties of various common construction and building materials used in the built environment and composing elements of buildings and infrastructures. In addition, suggestions and recommendations are made for the thermo-physical properties of the materials composing the indoor content and furniture elements present in the built environment [1][2]. This dataset and technical report are extensions of previous data collection presented in [3].

This dataset contains around 2100 different material lines. Some materials may have multiple entries with variations in the estimates of the thermo-physical properties. These variations between the different sources emphasize the difficulty to accurately determine the thermo-physical properties of building materials. In addition, these thermo-physical properties can vary significantly with temperature and humidity. For some material entries, only a part of the thermo-physical properties are indicated in the source and therefore compiled in this database.

The data has been aggregated from more than 100 different sources (scientific reports, scientific publications, technical documentation, online databases). It also includes measurement results from experimental investigations carried out at the Laboratory of Building Material Characterization (https://buildingmaterials.civil.aau.dk/) of Aalborg University (Denmark), Department of the Built Environment (https://www.en.build.aau.dk/).

Although it is relatively simple to find information about the density and thermal conductivity of many materials, the specific heat capacity, volumetric heat capacity, thermal diffusivity, relative gas diffusivity and effective gas permeability are much harder to find out. In addition, many materials in a given category are stated with generic round numbers for the specific heat capacity. This indicates that these data points are not accurately measured for a specific material but rather estimated for a whole category of materials (e.g., most of the woods are stated to have a specific heat capacity of exactly 1200 or 1600 J/kg.K).

The dataset can be found as an Excel sheet in the appendix of this report on https://vbn.aau.dk/.

One can also visualize the data with interactive figures on this website: https://therm-properties-build-mat.herokuapp.com/

2. Introduction

In thermodynamics and building physics, a good knowledge of the main material properties that play a major role in the heat, air and mass (HAM) transports is crucial to conduct proper design, sizing and simulations, and verify experimental measurements.

In this dataset, 7 material properties are collected:

- Density [kg/m^3]
- Thermal conductivity [W/m.K]
- Specific heat capacity [J/kg.K]
- Volumetric heat capacity [kJ/m^3.K]
- Thermal diffusivity [mm^2/s]
- Relative gas diffusivity [-]
- Effective gas permeability [m^2]

The dataset focuses on building materials used in the built environment and composing construction elements of buildings and infrastructures. The data entries are grouped into 17 distinct material categories:

- Insulating vacuum panel (although not being a material category per se)
- Aerogel
- Bio-based insulation
- Mineral insulation
- Polymer insulation
- Cellular glass/mineral
- Textile
- Paper / cardboard
- Wood
- Plastic/polymer
- Plaster
- Ceramic
- Structural material
- Natural stone
- Soil
- Metal
- Carbon structure
- Fiber/particle composite

Except if stated otherwise in the name of the material, the reported properties of the materials are assumed to be for ambient (room) temperature (10 °C – 40 °C), with normal conditions of pressure (atmospheric pressure) and relative humidity of around 50%. One should keep in mind that the thermo-physical properties of materials (especially porous materials) can be highly dependent on temperature and humidity.

3. Density Dependency of Many Building Material Properties

Many building materials are porous to some extent, meaning that they contain a certain fraction of pores that can be filled with dry or humid air (or other gases) or liquid water. The fraction of pores relative to the solid phase of the material and whether these pores are filled with dry air, humid air or liquid water can thus largely influence the density of the material but also its thermal conductivity, volumetric heat capacity, thermal diffusivity, relative gas diffusivity and effective gas permeability.

There is a strong correlation between the density and thermal properties of porous materials such as thermal conductivity (bulk metals and ceramics are not porous and thus do not present such a trend). The thermal conductivity of porous building materials is mainly determined by the solid phase fraction/porosity (and thus density), and the air and water content of these pores. Higher porosity materials (lower density) with air-filled cavities have fewer and smaller solid-phase bridges that conduct heat better than air/gas, and many air/gas-filled cavities with low thermal conductivity. This drives the overall effective thermal conductivity of the porous material down. If the conductive solid-phase fraction is larger, the density and the thermal conductivity tend to increase. If the cavities of the materials are filled with liquid water, the overall humidity content of the material increases together with its density (because liquid water is much denser than air/gas) and its thermal conductivity (because liquid water is much more conductive than air/gas and forms highly conductive bonds/bridges within the solid-phase matrix of the porous material). One can thus observe that, in general, building materials with a high density have larger thermal conductivity than building materials with a lower density (some exceptions are discussed in this report).

Because of this general correlation between density and other material properties, the data is presented in this report as a series of figures showing a given material property as a function of the density. However, one can note that the correlations between the density and the other material properties are not always positive, linear and/or monotonic. Although much weaker, these correlations can hold when looking at the overall dataset, but can change significantly or disappear when looking at the data points within a specific material category: e.g., the correlation between density and thermal conductivity is negative for ceramics and very weak but negative for metals.

4. Overview of Building Material Properties

4.1. Density

One can see in *Figure 1* that the density of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible density for each material category.

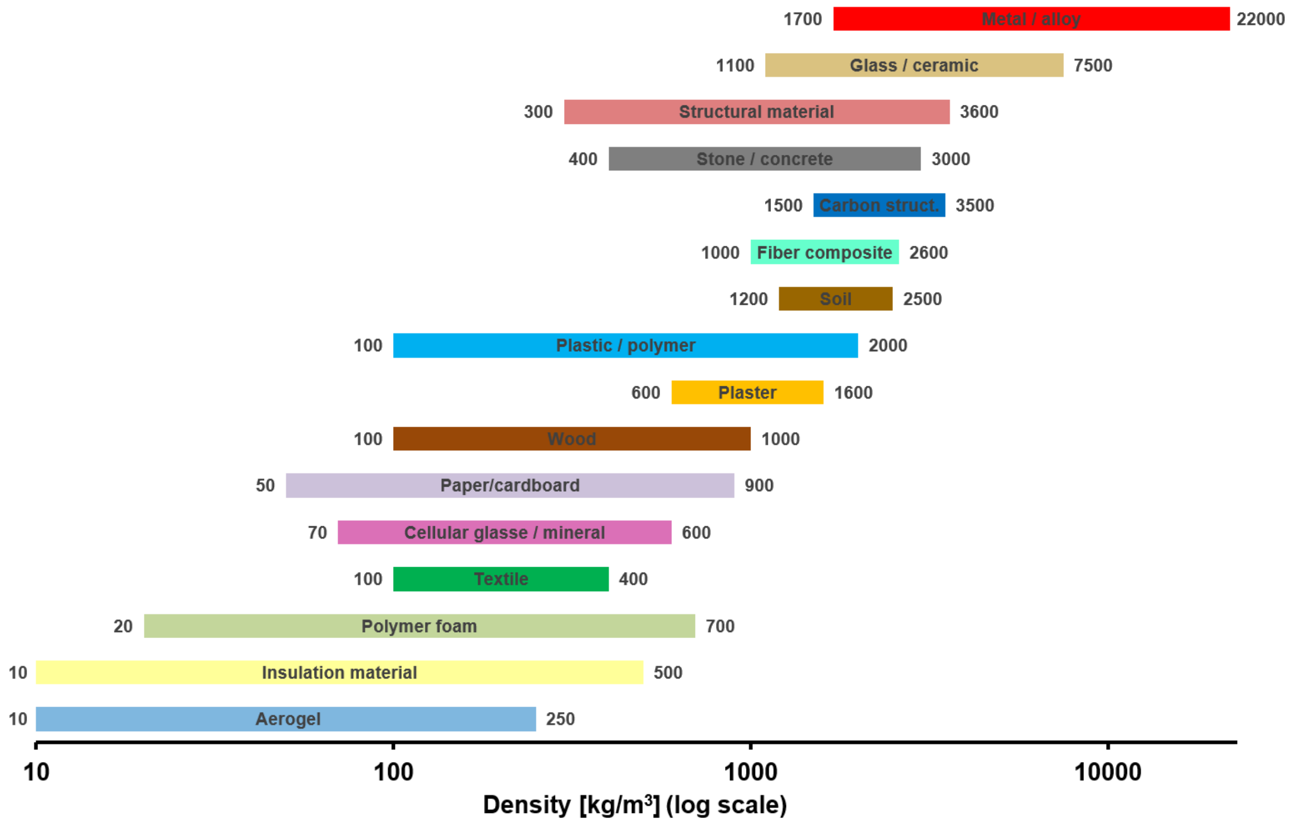

Figure 1: *Density of building materials (log scale).*

4.2. Thermal Conductivity

One can see in *Figure 2* that the thermal conductivity of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible thermal conductivity for each material category.

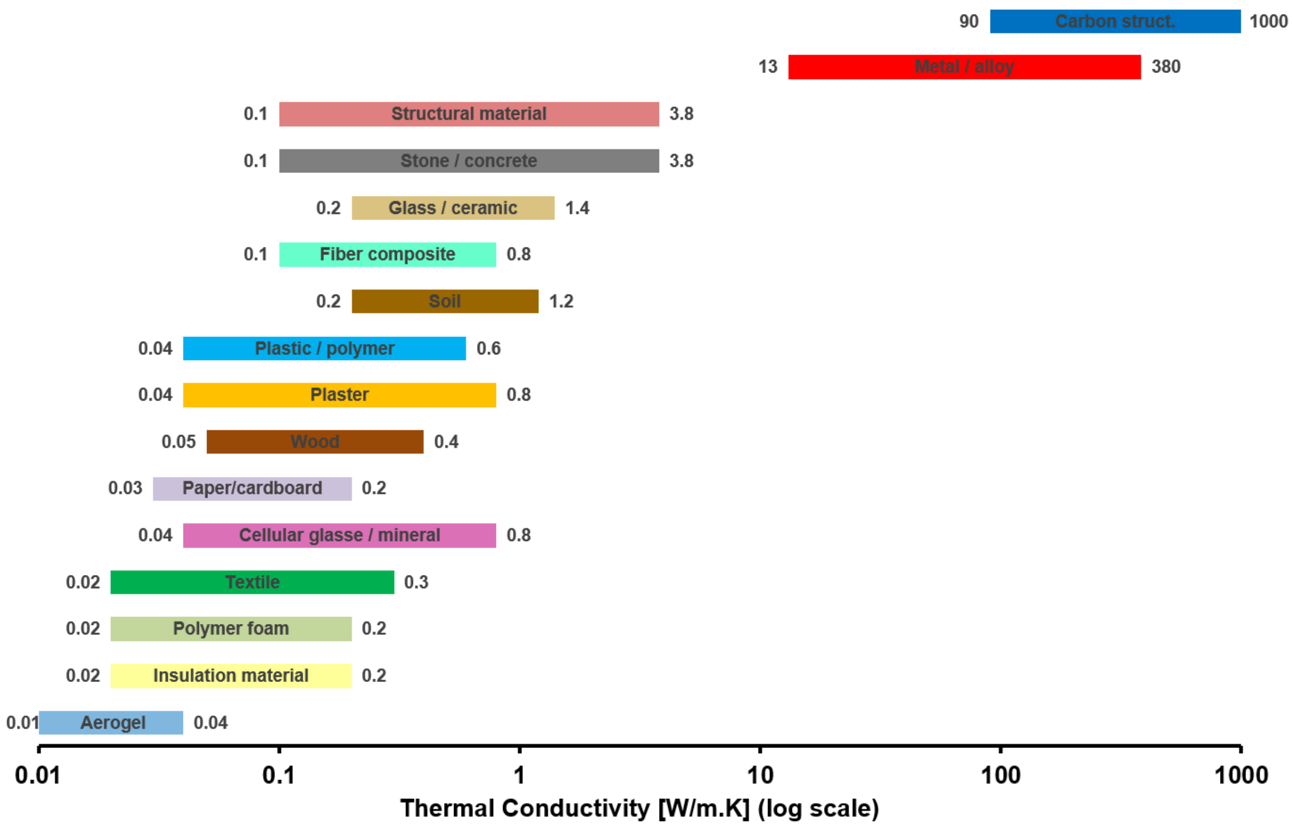

Figure 2: *Thermal conductivity of building materials (log scale).*

As illustrated in *Figure 3*, *Figure 4*, *Figure 5*, *Figure 6* and *Figure 7*, there is a clear positive correlation between material density and thermal conductivity, especially for building materials with a density below 3000 kg/m^3. However, this correlation is negative for the ceramics and glass materials, and very weak for metals. This can be explained by the fact that these material categories are not porous materials and their thermal properties are driven by different phenomena than that of porous material categories.

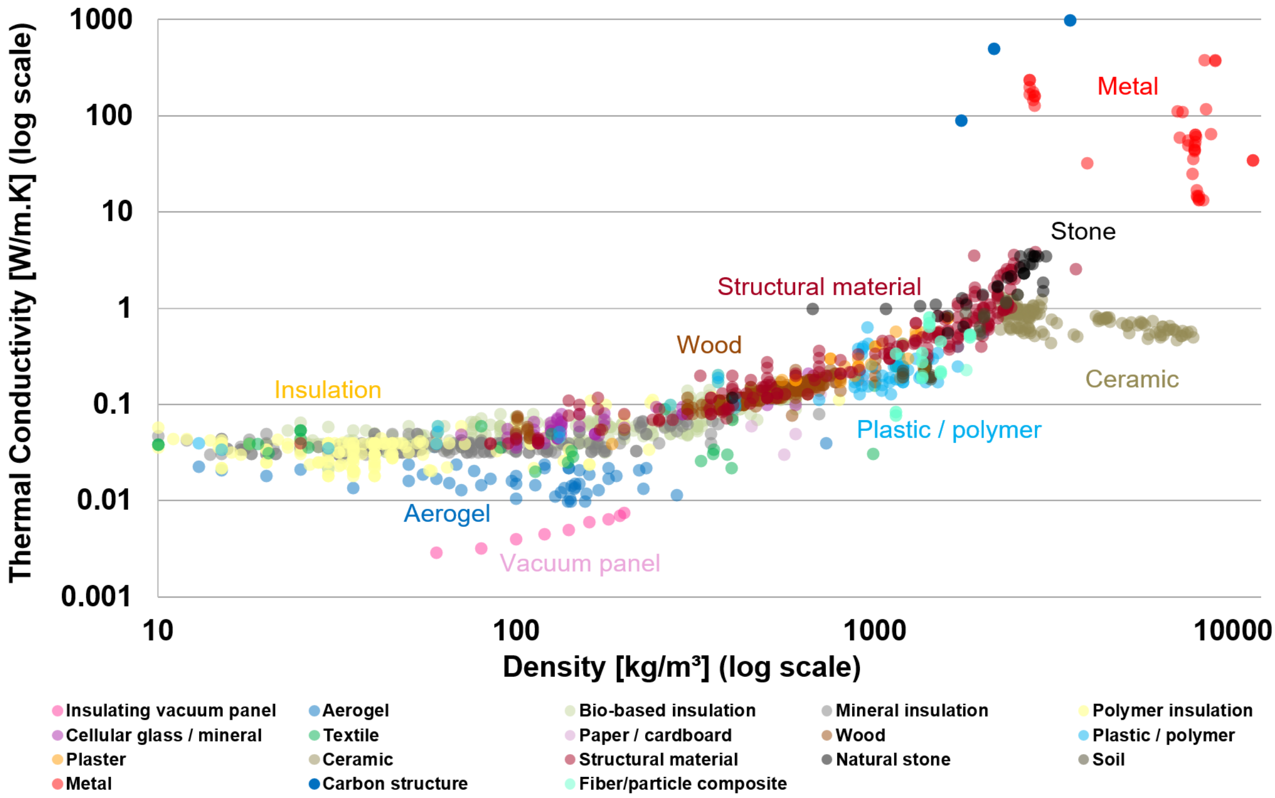

Figure 3: *Thermal conductivity as a function of density for building materials (log-log scale).*

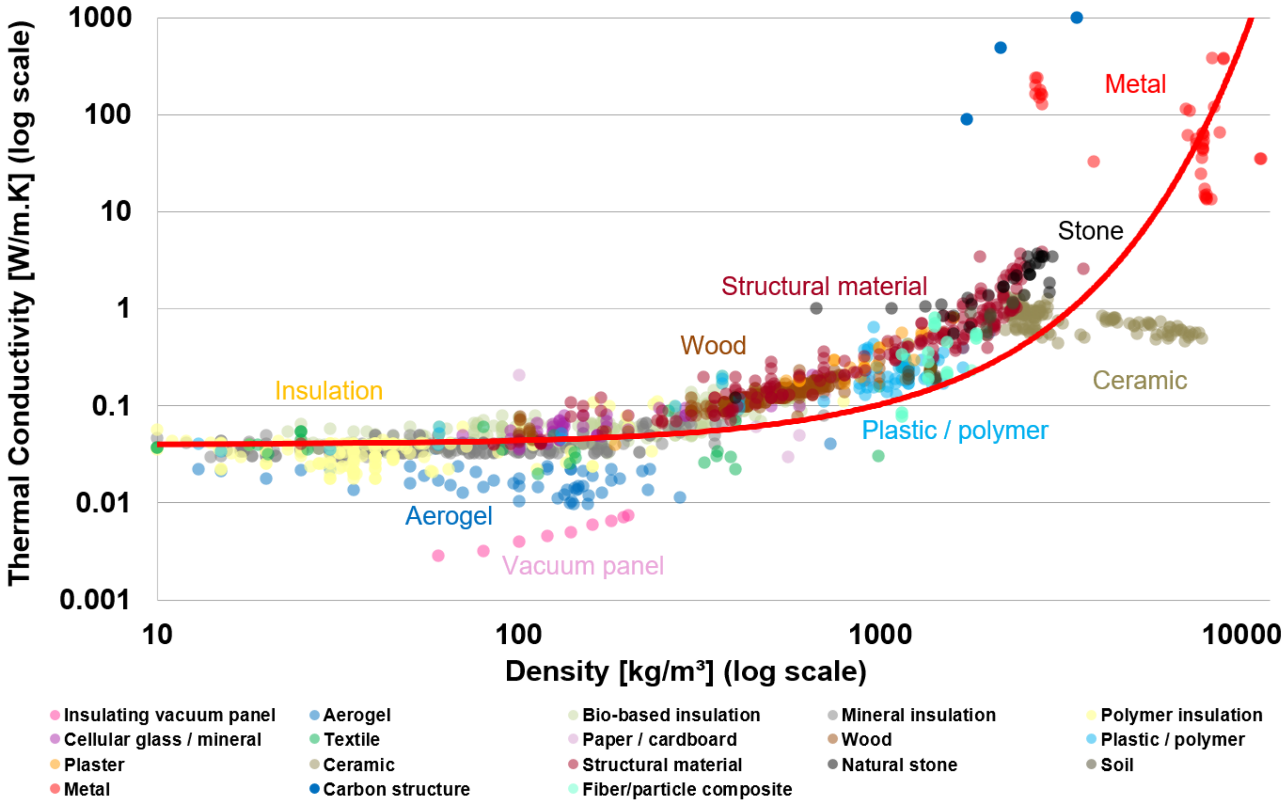

Figure 4: *Thermal conductivity as a function of density for building materials (log-log scale).*

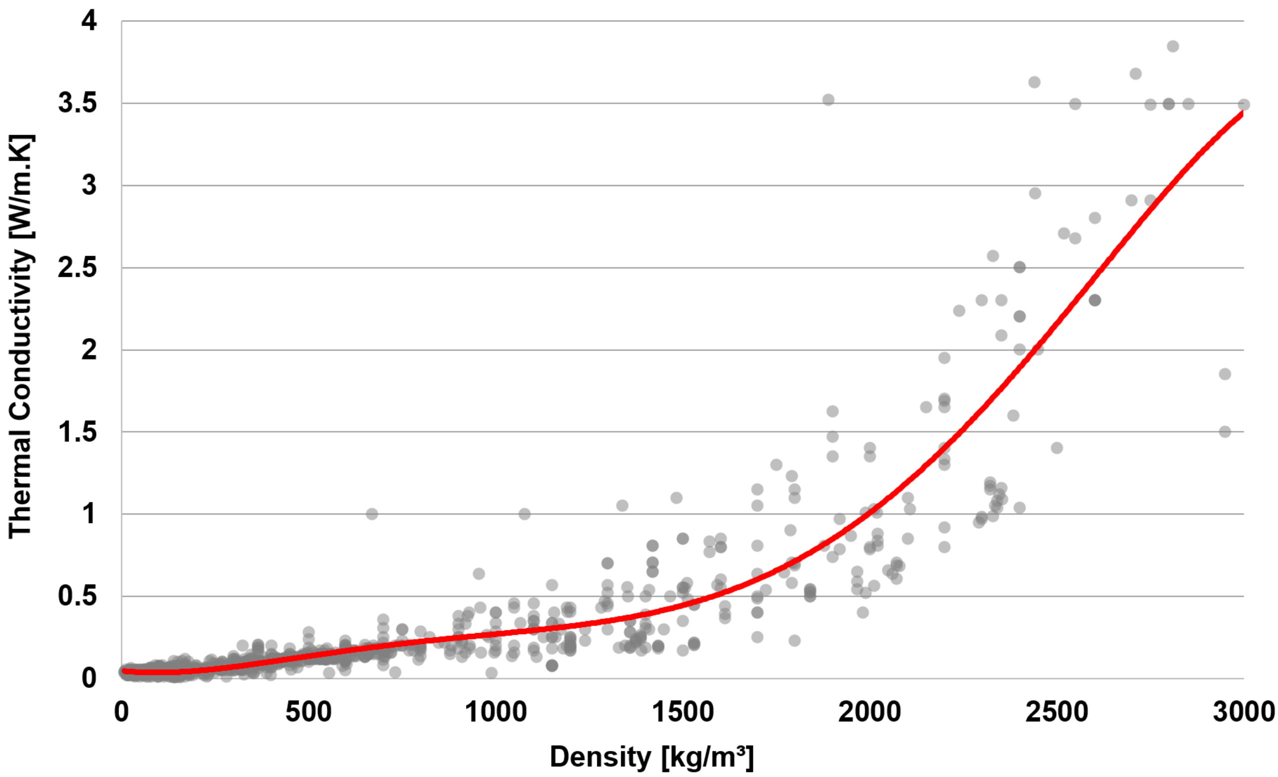

Figure 5: *Thermal conductivity as a function of density for building materials with a density below 3000 kg/m³.*

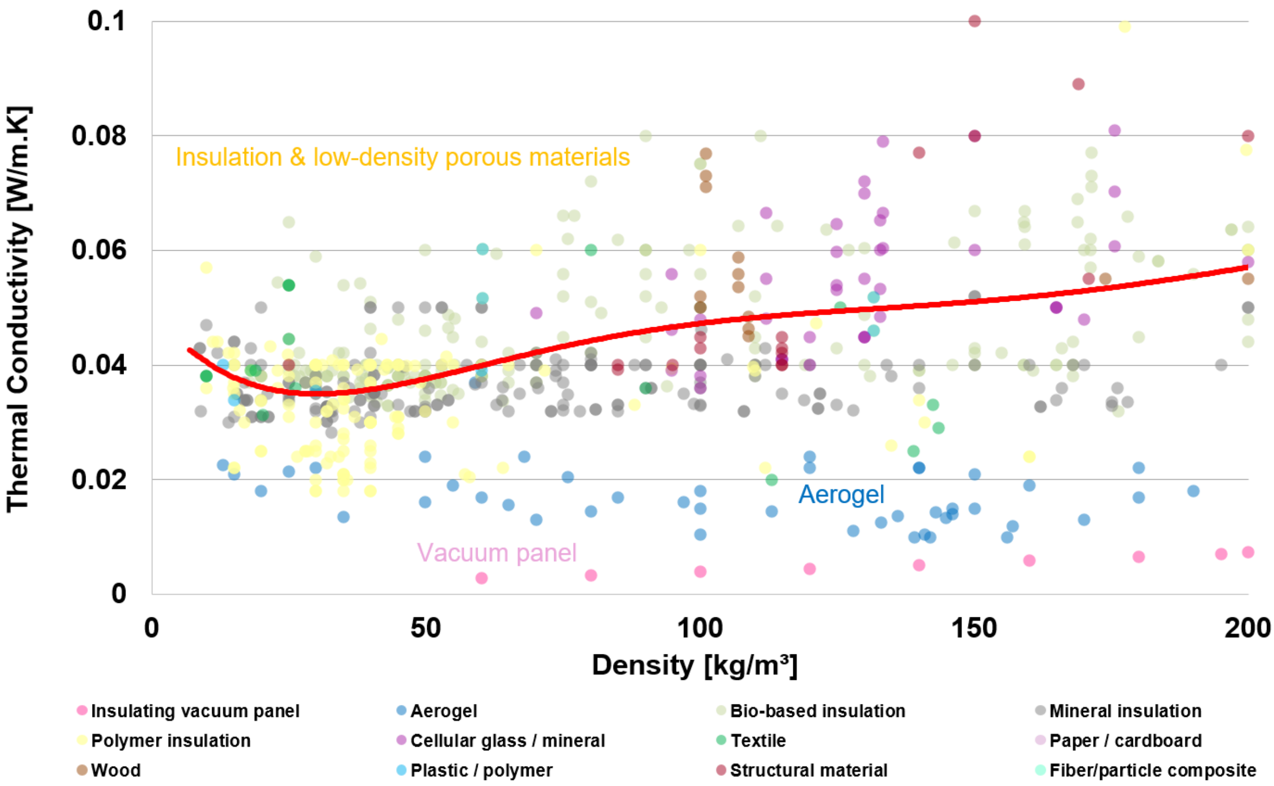

Figure 6: *Thermal conductivity as a function of density for low-density building materials.*

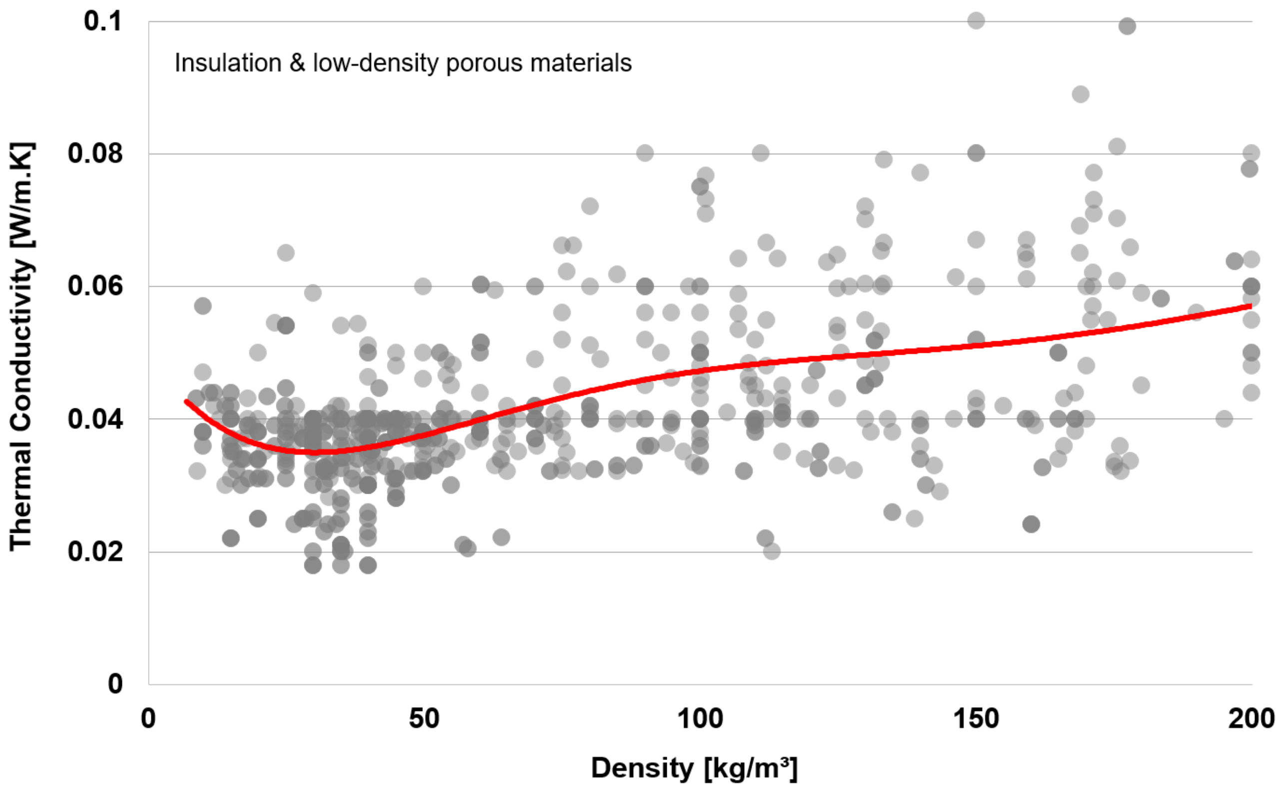

Figure 7: *Thermal conductivity as a function of density for low-density building materials (excluding aerogels and insulating vacuum panels).*

One can see in *Figure 6* and *Figure 7* that for insulation porous materials (excluding aerogels and vacuum panels) there is an optimum density (around 30 - 50 kg/m^3) for which the thermal conductivity tends to be minimum. For a density lower than 30 - 50 kg/m^3, the thermal conductivity tends to increase slightly with decreasing density.

This negative correlation between density and thermal conductivity below a critical point can be explained as follows:

- Above the critical point (higher density) the overall heat transfer driving the effective thermal conductivity of the porous material is conduction through the solid phase. Therefore, the lower is the density, the more air-filled cavities are present in the material and thus the fewer solid-solid conductive bridges exist (*Figure 8* right side).
- Below the critical point (lower density) although decreasing density reduces the number and size of the solid-solid conductive bridges, the air-filled cavities are getting larger. Above a certain size, convection becomes significant in those air-filled cavities, which drives the effective thermal conductivity of the porous material up (*Figure 8* left side).

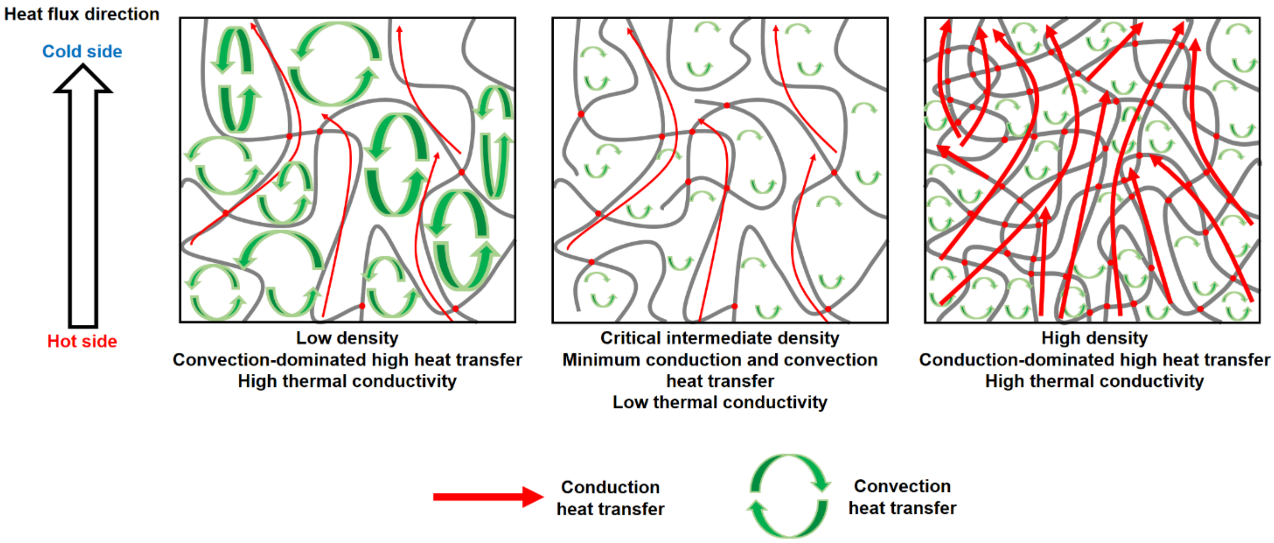

Figure 8: *Different heat transfer modes driving the effective thermal conductivity of porous insulation materials around the critical compactness density point [38].*

The trend described above is, however, not applicable to aerogels. Aerogels have extremely high porosity and thus low density but also present ultra-low thermal conductivity (down to 0.01 W/m.K). Nevertheless, aerogels alone are fairly brittle and expensive and require to be incorporated into other tougher materials to ensure certain durability for building applications.

4.3. Specific Heat Capacity

One can see in *Figure 9* that the specific heat capacity of building materials is often within the 300 – 2500 J/kg.K range. The figure provides information about the range of possible specific heat capacity for each material category.

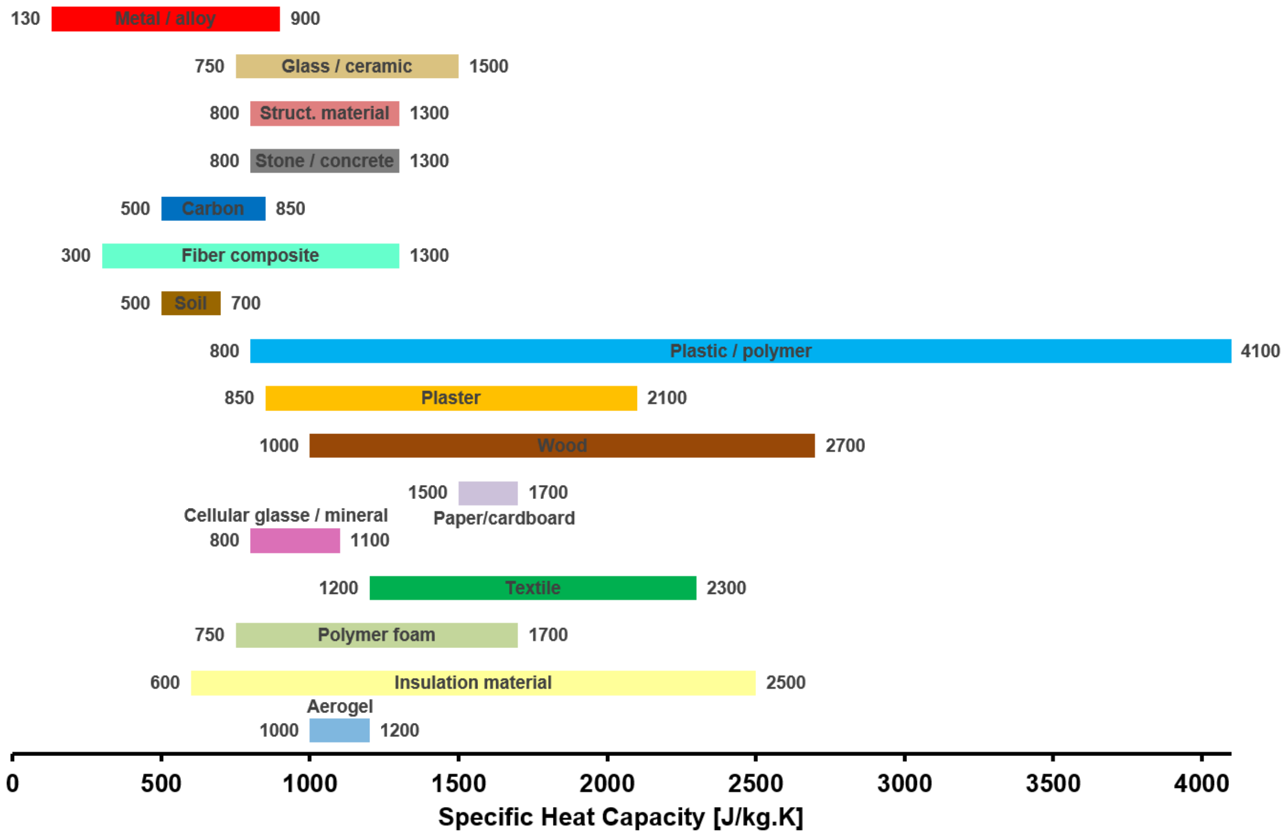

Figure 9: *Specific heat capacity of building materials.*

One can see in *Figure 10* that there is no strong correlation between the density and the specific heat capacity of common building materials.

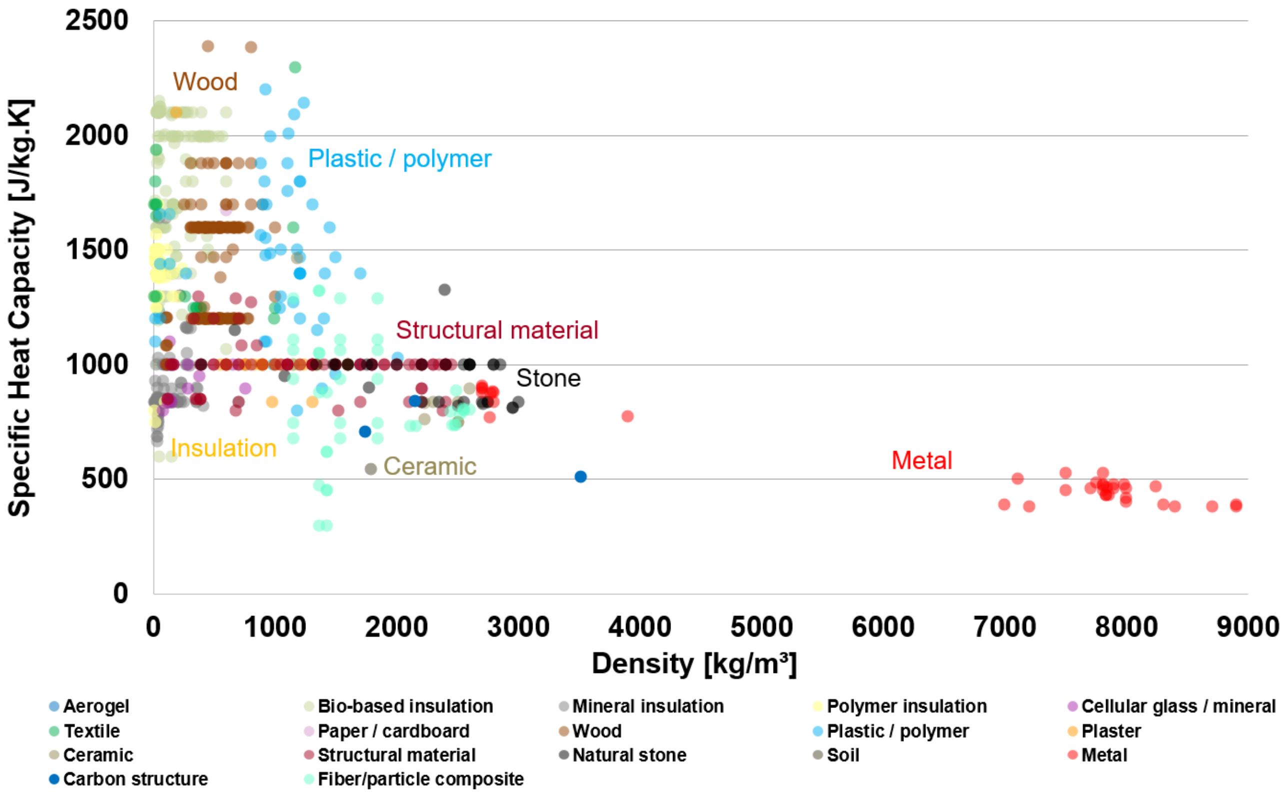

Figure 10: *Specific heat capacity as a function of density for building materials.*

4.4. Volumetric Heat Capacity

Similarly to the density, one can see in *Figure 11* that the volumetric heat capacity of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible volumetric heat capacity for each material category.

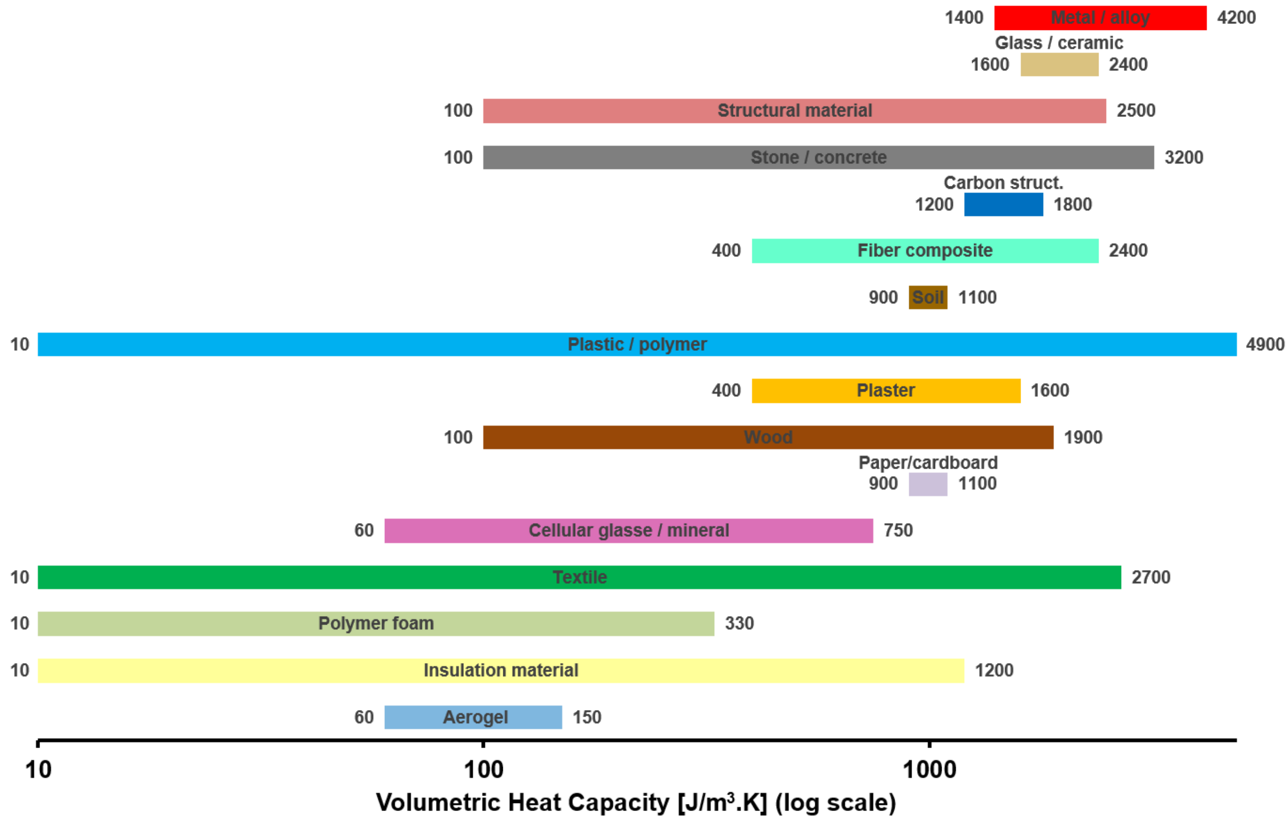

Figure 11: *Volumetric heat capacity of building materials (log scale).*

One can see in *Figure 12* that there is a strong correlation between the density and the volumetric heat capacity of common building materials, which can easily be explained because volumetric heat capacity is directly proportional to density (and specific heat capacity).

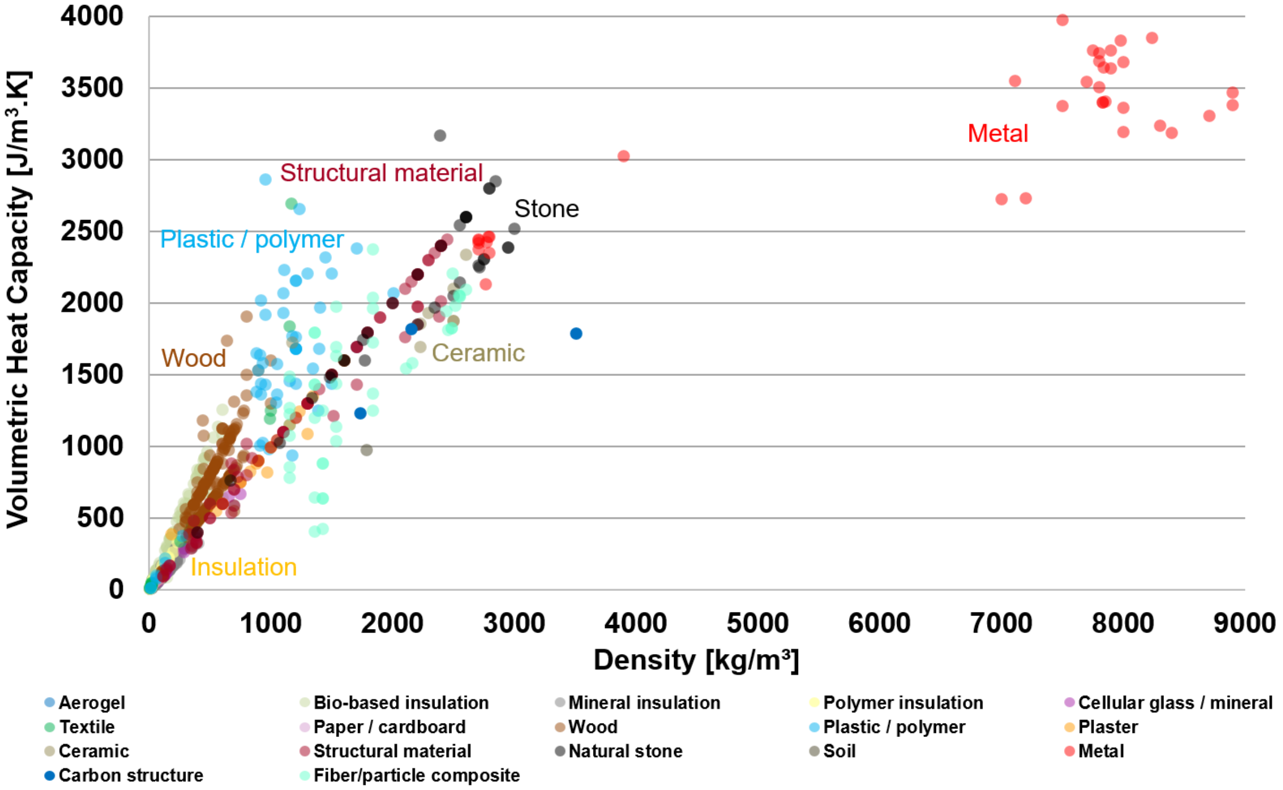

Figure 12: *Volumetric heat capacity as a function of density for building materials.*

4.5. Thermal Diffusivity

One can see in *Figure 13* that the thermal diffusivity of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible thermal diffusivity for each material category.

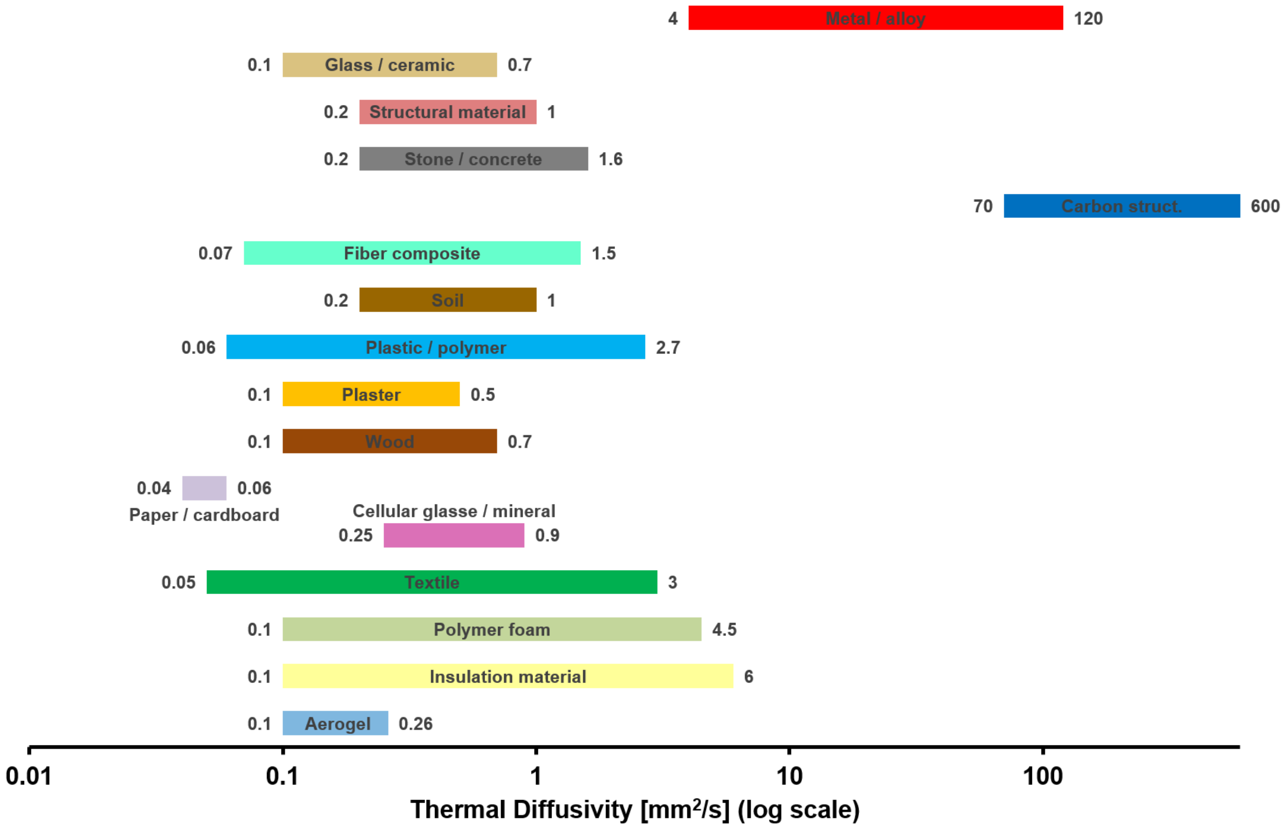

Figure 13: *Thermal diffusivity of building materials (log scale).*

One can see in *Figure 14* that there is a non-monotonic correlation between the density and the thermal diffusivity of common building materials, which is logical since thermal diffusivity is correlated to the thermal conductivity, density and specific heat capacity which, themselves, are correlated to density.

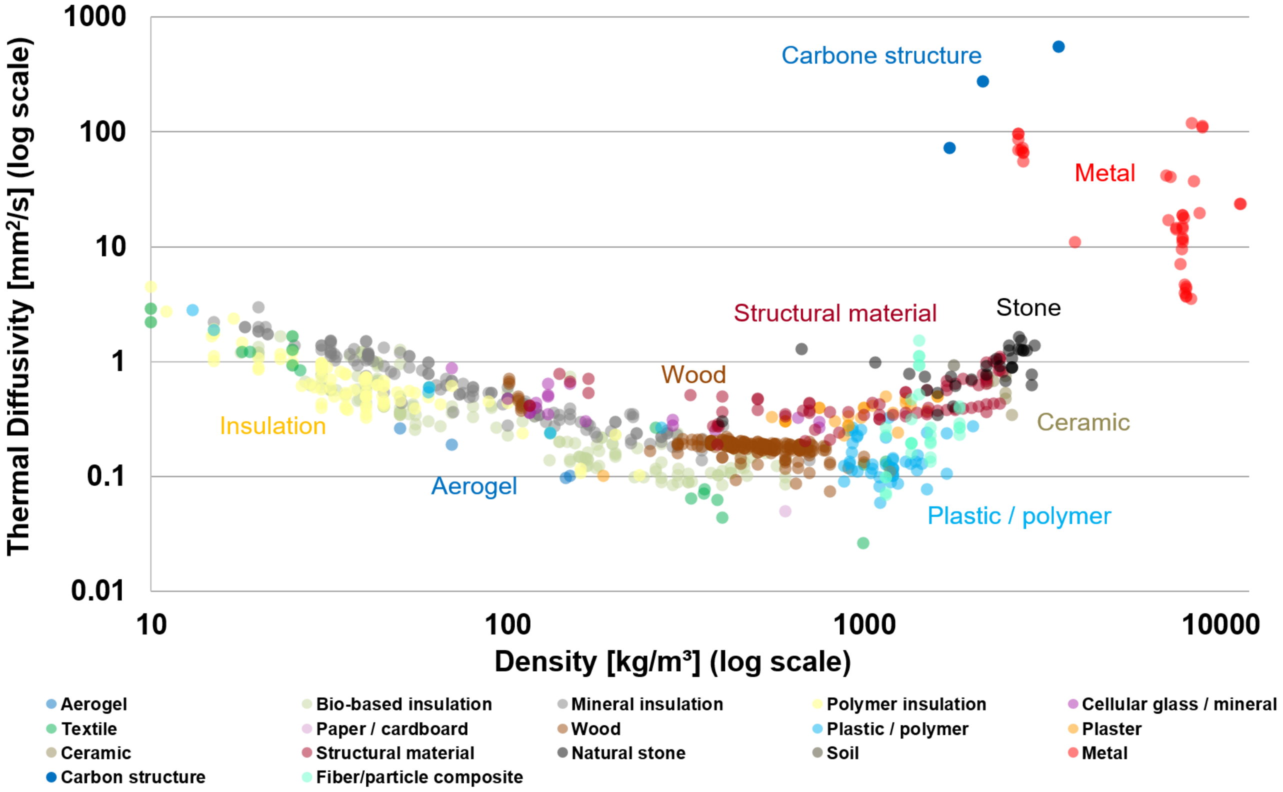

Figure 14: *Thermal diffusivity as a function of density for building materials (log-log scale).*

4.6. Effective Gas Permeability

One can see in *Figure 15* that the effective gas permeability of insulation materials spans over a very wide range of several orders of magnitude: from 10^{-10} to 10^{-6} m^2. In addition, one can observe a negative correlation between material density and effective gas permeability, which can be explained by the fact that insulation materials with higher density have higher compactness and thus offer fewer and narrower free paths (open channels or cavities) for the gas to flow through.

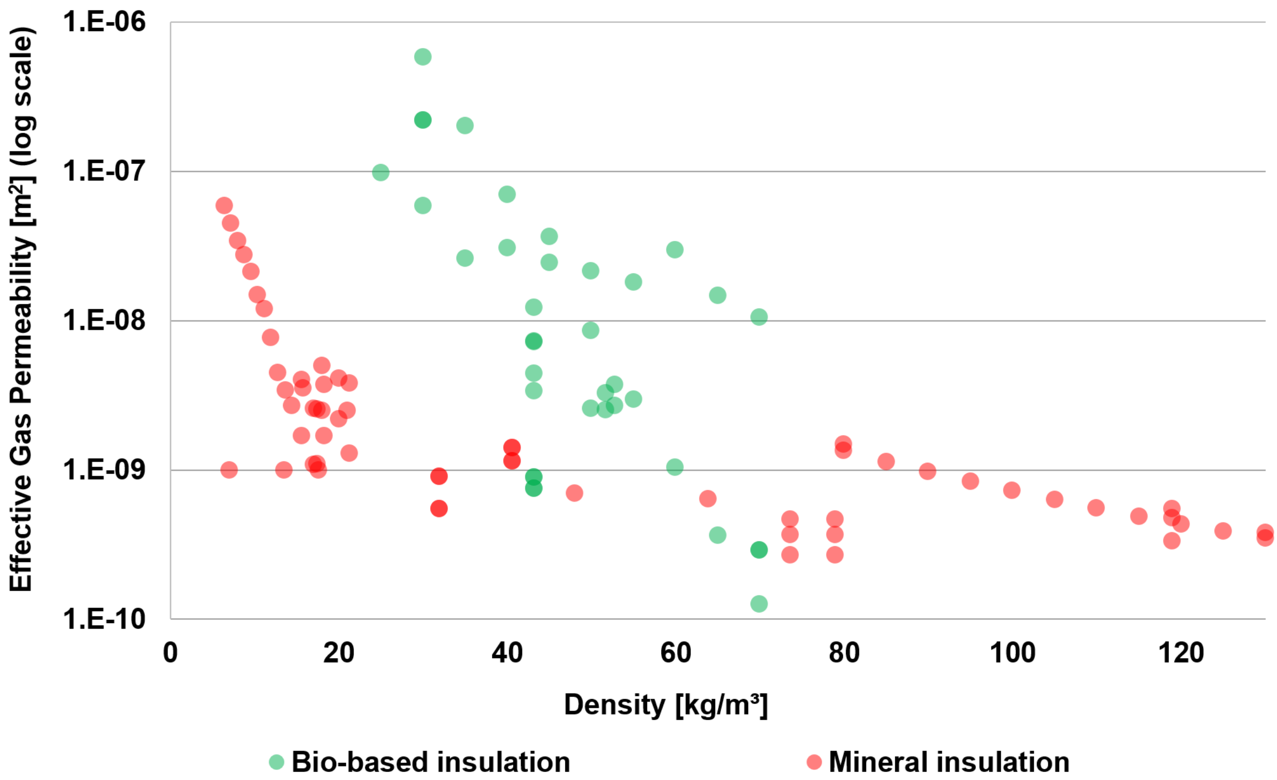

Figure 15: *Effective gas permeability as a function of density for building materials (log scale).*

5. Thermo-Physical Material Properties of the Indoor Content and Furniture Elements

The indoor content and furnishing elements present inside the built environment often have complex geometries with various types of material. One can find in Table 1 recommendations for the thermo-physical properties of these indoor content elements. It is considered that the materials composing the indoor content elements can be classified into 4 main categories: light material, wood/plastic material, concrete/glass material, metal material. In addition, the properties of an equivalent indoor content material (which would therefore account for the equivalent thermo-physical properties of the overall indoor content elements) is given. For all categories, indications on the dimensions, effective thermal inertia and amount in buildings (mass relative to floor surface area) are given. These recommendations are valid for both residential and office buildings [1][2].

Table 1: *Thermo-physical properties of the representative indoor content material categories [2].*

Material category	Room mass content (kg/m² floor area)	Surface area (m²/m² floor area)	Material density (kg/m³)	Material thermal conductivity (W/m.K)	Material specific heat capacity (J/kg.K)	Planar element thickness (cm)	Daily effective thermal inertia (kJ/K.m² floor area)
Light material	7 (0.5–14)	0.3 (0.1–0.6)	80 (20–140)	0.03	1400	10 (0.5–24)	3 (0.2–7)
Wood / plastic material	30 (8–80)	1.4 (0.5–2)	800 (400–1200)	0.2 (0.1–0.3)	1400	1.8 (1–5)	26 (9–45)
Concrete / glass material	1 (0.5–2)	0.03 (0.01–0.04)	2000 (1500–2500)	1.25 (0.5–2)	950	1 (0.2–2)	0.1 (0.05–0.2)
Metal material	2 (1–5)	0.02 (0.01–0.03)	8000	60	450	0.2 (0.1–0.3)	0.1 (0.05–0.4)
Equivalent indoor content material	40 (10–100)	1.8 (0.8–2.8)	600 (150–1500)	0.3 (0.1–0.5)	1400	4 (1–10)	30 (10–50)

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