Characteristics of Construction Materials: Thermal Expansion and Cooling Behaviours

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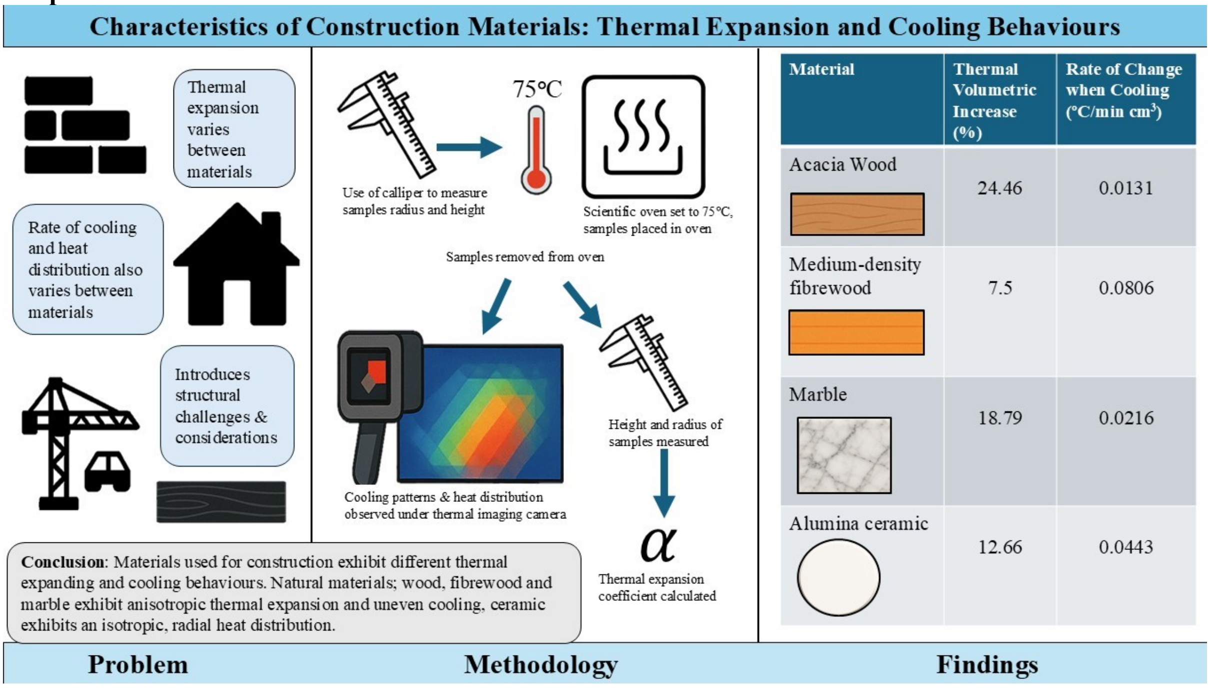
Graphical Abstract



Characteristics of Construction Materials: Thermal Expansion and Cooling Behaviours

Thermal expansion varies between materials

Rate of cooling and heat distribution also varies between materials

Introduces structural challenges & considerations

Use of calliper to measure samples radius and height

75°C

Scientific oven set to 75°C, samples placed in oven

Samples removed from oven

Cooling patterns & heat distribution observed under thermal imaging camera

Height and radius of samples measured

α

Thermal expansion coefficient calculated

Conclusion: Materials used for construction exhibit different thermal expanding and cooling behaviours. Natural materials; wood, fibrewood and marble exhibit anisotropic thermal expansion and uneven cooling, ceramic exhibits an isotropic, radial heat distribution.

Material	Thermal Volumetric Increase (%)	Rate of Change when Cooling (°C/min cm^3)
Acacia Wood	24.46	0.0131
Medium-density fibrewood	7.5	0.0806
Marble	18.79	0.0216
Alumina ceramic	12.66	0.0443

Problem **Methodology** **Findings**

Abstract

Thermal expansion has been an issue that led to multiple challenges in fields such as transport and construction for many years. Accounting for this is an essential component of selection and usage of many materials, with the degree of uniformity to which materials expand is a centrepiece in designing products. The usage of a heat visualisation cameras allows for accurate mapping of the distribution of heat within a material and identify the uniformity of cooling and suggest the presence of uneven thermal expansions, the source of thermal stresses.

Experimental testing allowed for the modelling and analysis of isotropic and anisotropic expansion, whereby wood was found to have the highest coefficient of thermal expansion (α), indicating that when exposed to temperature variations, the change in atomic length was the largest in this material. However, experimental and theoretical α values had significant discrepancy, pointing to inaccuracy due to hygroscopic behaviour of samples and other errors. Material choice for industrial and construction applications is directly dependent on the thermal characteristics and behaviour of the material. The experiment found that Wood had the highest heat retention rate, therefore useful for insulation and structural applications. Further, the fibreboard had the lowest retention and highest rate of cooling, indicating its usefulness in rapid cooling situations and temperature stabilisation.

Keywords: Coefficient of Thermal Expansion, Isotropic, Anisotropic, Heat distribution, Homogenous

1. Introduction

Thermal expansion is the tendency of a material change in size in response to temperature changes, whereby in most cases increased temperatures induce a dimensional expansion and decreased temperature results in a dimensional contraction of a given substance. In solids this phenomenon occurs through the solid-state lattice arrangement of particles and the interatomic anharmonic potential[1] of a substance. From collision theory, as temperatures rise, thermal energy supplied causes an increase in kinetic energy, resulting in increased particle vibrations and average interatomic separation[2].

Thermal expansion of solids can be observed in respect to length, area, and volume, whereby either uniform expansion (isotropic expansion) or direction dependent expansion (anisotropic expansion) occurs. The linear thermal expansion coefficient (α_l) quantifies the degree at which a solid's respective lengths due to temperature changes. This coefficient can also be considered in terms of volume and area changes. The formula for α_l is seen below.

$$\alpha = \frac{1}{L_{initial}} \cdot \frac{dL}{dt}$$

Furthermore, observations of the heat distribution along the surface of a material as it cools is useful for identifying the usage of various materials in different contexts. Non-uniform thermal cooling can be a result of anisotropic crystalline structures or a nonhomogeneous material composition, which can lead to significant thermal stresses within a material due to variations in thermal expansion along different directions. This theory plays an essential role in many fields such as construction where thermal stresses can be highly hazardous and compounded when materials are under external stresses. Furthermore, electronics rely on consistent uniform crystalline structures for repeatability and reliability as well as dissipating heat efficiently and quickly. This naturally extends to a quantitative analysis of the volumetric ability of a material to lose heat rather than a qualitative analysis of distribution. This essential in deciding appropriate materials in heating and cooling applications such as insulation within constructions. Using a thermal camera has the advantage of analysing a map of the heat and thus the uniformity or lack of temperature within a material.

2. Methods

Experimental testing sought to quantitatively measure thermal expansion and rates of cooling for circular samples of wood, marble, ceramic, and medium density fibreboard. This was achieved through measuring the difference in diameter and height of the samples once reaching 75°C. Once this occurred, thermal cameras were then employed to measure heat loss throughout each sample, with measurements been taken over a 10-minute period. Prior to heating, measurements of the diameter and height of the 4 different materials were taken using a calliper to optimise accuracy.

The procedure involved heating the samples in a laboratory oven to 75°C, this was done at the same time to ensure reliable and uniform thermal exposure for all 16 samples. However, this was somewhat limited by the oven set up, whereby some samples were placed at the top of the oven and some at the bottom, which would have impacted the consistency of heat flux applied to each sample. Once the oven had been consistently at the desired temperature for fifteen minutes, each sample had its dimensions measured using the same calliper, this was used to quantify any thermal-induced expansion. Once all 16 samples had their dimensions measured and back up to the desired temperature, further testing was used to focus on cooling tendency and heat distribution. The experimental set up used can be seen in figure 1.

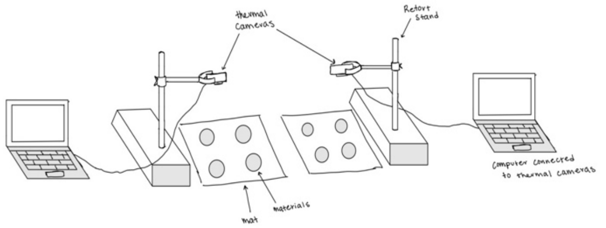


Figure 1: *Scientific drawings of experimental set up and equipment used*

To assess the distribution of thermal energy during cooling and heat loss, measurements were recorded at 1-minute intervals over a 10-minute duration through the thermal camera. The experimental setup can be seen in figure 1, whereby the thermal camera was placed vertically above the samples held by a clamp to ensure a consistent field of view. Specific temperature readings were taken for each sample, whereby measurements were taken at the centre, around the circumference, and across the radius. The data collected consisted of multiple temperature readings as well as a photo of the overall temperature distribution. These measurements provided a time-resolved data set of heat loss across each material surface and provided qualitative evidence of the differing ways heat travelled through each medium.

All the data collected in the experiment was then analytically studied, through various statistical methods, to draw accurate and reliable conclusions. The raw data of such can be found in the appendix, and notable graphs and tables will be found further in the report.

3. Results and Discussion

3.1 Thermal Expansion

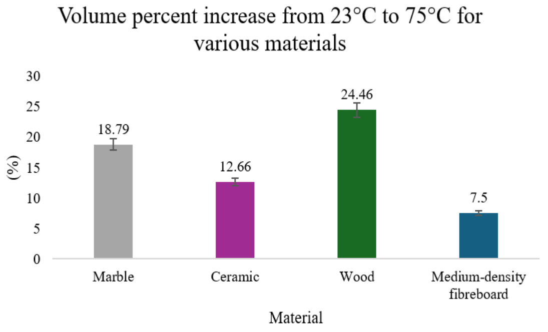


Figure 2*: Bar graph for percentage volume increase of four tested materials when heated to 75°C*

Volume was defined as $V = \pi r^2 h$, assuming perfect cylindrical shape and uniform expansion across each material's radius and height. The results indicate that wood has the highest volume change from room temperature to 75°C), with marble then ceramic, and medium-density fibreboard experienced the lowest degree of expansion. The extent to which different materials thermally expand is dependent on atomic structure and intermolecular forces as well as material homogeneity.[3]

Thermal expansion varies between materials primarily as a result of increased particle separation, either due to increased bond length between atoms or cell wall swelling. The coefficient of thermal expansion is a material-specific property quantification of this, indicating the extent to which different materials expand or contract at the same temperature, in this situation it has been defined as the fractional increase in length per unit rise in temperature[4].

$$\alpha = \frac{\Delta L}{L_{initial} \times \Delta T} \tag{1}$$

Table 1: Comparison of calculated linear thermal expansion coefficients from experimental procedure versus theoretical linear thermal expansion coefficients[5]

Material	***ΔL***	***ΔT***	***α (Experimental)***	***α (Theoretical)***	***Percentage Difference***
	m	***°C***	***$°C^{-1}$***	***$°C^{-1}$***	***(%)***
Marble	0.00257	52	0.000486	0.0000141	3350
Ceramic	0.00250	52	0.000465	0.0000081	5640
Wood	0.00252	52	0.000483	0.00003	1510
Medium-density fibreboard	0.00248	52	0.000478	0.0000003	160000

Example calculation for marble length expansion 75°C

$$\alpha = \frac{0.00257}{0.102 \times 52} = 0.000486/ºc$$

3.1.1 Uncertainty

It should be acknowledged that the experimental procedure does hold potential uncertainty. A calliper was used to measure the radius and height, which had a resolution limit of 0.01mm and hence a measurement of 1mm has an uncertainty of +/-0.005mm. This corresponds to a percentage uncertainty of 0.5%, which is reasonably small and unlikely to pose any significant uncertainty in recorded data. However, since the small scale of the measurements, uncertainty is higher than in a larger scale situation. Further to this, potential human error could have arisen from inaccurate calliper placement, whereby the calliper was not in the centre of the circular objects nor consistently in the same position for each measurement. The laboratory oven used is regularly calibrated to ensure that the internal temperature matches that displayed, however the potential for this inconsistency remains as the experimental procedure did not use a thermometer to confirm internal temperature of the oven or the material. Furthermore, humidity was not controlled therefore a constant moisture content was not achieved in the conditions of which the samples were being tested. This resulted in some samples having a higher moisture content and therefore hygroscopic behaviour which reduces accuracy and reliability of the calculated expansion coefficient.

3.1.2 Material composition & purity

The materials used; acacia wood, alumina ceramic, marble and medium-density fibrewood, cannot definitively said to be of 100% purity as this was not tested prior to experimental procedure. While materials of high purity and isotropic structure typically exhibit a relatively uniform thermal expansion due to consistent atomic bonding and vibrational energy, impurities or amorphous components—such as lignin and other structural proteins in wood—can disrupt this uniformity, influencing thermal expansion behaviour~~.~~ beyond just structural considerations. Impurities can often result in anisotropic thermal properties, whereby the thermal conductivity differs in various directions[6], producing a non-uniform profile or a thermal expansion coefficient inconsistent with theory. This is particularly true for wood samples, such as the acacia wood used in this procedure, where typically smaller samples are not fully representative of the behaviour of engineered timber products at larger scales due to the present of annual rings or the stacking arrangement of wood planks[7]. This theory is a plausible explanation for the wood's deviation from the theoretical value of 0.00003 (m/m×°C) by 15.09 times. Further to this, typically marble samples are primarily composed of 90-99% calcite,

$CaCO_3$, as well as dolomite and serpentine[8]. The 33 times difference between marbles' theoretical coefficient 0.0000141 (m/m×°C) and the experimental coefficient suggests variation from assumed purity levels; likely the material was composed of materials in high quantities other than calcite such as quart or resins. The same can be said for the alumina, Al_2O_3, ceramic and medium-density fibreboard, considering they deviated by 56 and 159 times, respectively, from the theoretical quantity. However, considering the small scales of the coefficients, that the absolution magnitude of the deviations appears larger than they physically area.

Wood and marble were found to have the largest thermal expansion coefficient in the x direction (length of the sample) with values around 0.00003 and 0.000141 respectively. These are higher than the coefficient for medium-density fibreboard due to the presence of pores within the fibreboard, diluting the volumetric change as the pores somewhat hide this. This is due to the particles expanding into the pores of the material before out of the original dimensions. The readings taken within the lab of volume through measuring length is not reflective of the actual volume of the fibreboard itself, as this formula assumed porosity was not apparent within the solid. As such, volumetric displacement would give a higher accuracy measurement and thermal expansion coefficient, however, this is not applicable in large scaler industry and is not a feasible process in this way.

The significant discrepancy between theoretical and experimental α values can be primarily attributed to high moisture content trapped within the materials, otherwise known as hygroscopic behaviour, which can be exacerbated in high humidity environments. Hygroscopic materials will experience distortion of dimensional and thermal properties, such as the coefficient of thermal expansion, heat capacity and volume. The effect moisture content has directly depended on the composition of the material, specifically the difference between the cellulous wood and the non-cellulous other samples. Wood does not have a constant equilibrium moisture content, whereby water within the material can be free and in the cell cavities or bound and within the cells themselves, as such the evaporation of water particles into pressure increasing gases does not occur. Instead, the rate of cell wall swelling increases with moisture content by 5-25% until the fibre saturation point occurs, where after this point the rate significantly declines due to capillary condensation[7]. As such, wood has the highest α value and volumetric expansion yet the lowest discrepancy between the experimental and theoretical ones.

Furthermore, studies suggest that during thermal cycling, the process of stressing and relaxing the material, cause changes to the microstructures of the material which as more cycles are perform stabilise out. This influences properties such as the thermal expansion coefficient which would be expected to deviate significantly from the tested values during an initial cycle.[9] If many cycles were performed, the thermal properties should converge to those found in literature as the nanostructures within the material begin to reach a more stable state due to the constant stress and relaxation[10].

For certain porous or hygroscopic materials, rising temperatures causes the kinetic energy of trapped water molecules within the material to increase. As the energy of particles rise, they spread out more and water undergoes a phase change from the liquid to gaseous state, generating internal pressure forces within the pores of the material and leading to expansion. This occurs to a greater extent in materials with a high moisture content and low porosity, as there is no open spaces for this gas to occupy This occurrence within the measurements lead to the significant overestimation of the expansion coefficient, as this is not due to atomic vibration which thermal expansion is defied by, rather pressure driven volumetric change. As such, it can be assumed the experimental coefficient combines this as well as atomic vibration. The effect of this was largest in the fibreboard, whereby despite its porosity, it can be assumed that it had a high moisture content which caused the largest discrepancy between its actual and experimental α value.

Conversely, the manufactured fibreboard is characteristically dimensionally stable[11] when exposed to most moderate ranging temperatures such as general temperature cycles throughout the year. However, it is very sensitive to moisture and moisture induced swelling occurs, this theory supports the assumption that the fibreboard was significantly moist, accounting for the largest difference between actual and experimental results, whereby the results calculated were distorted by dimensional and volumetric expansion. Similarly, ceramics also have a low thermal expansion and exhibited moisture-related expansion in the same way that fibreboard did, just to a lower extent

3.1.3 Anisotropic vs Isotropic

Materials tend to respond differently when exposed to high temperature environments, whereby the expansion and general material properties may be considered anisotropic or isotropic. Isotropic expansion describes a material in which has a constant linear thermal expansion coefficient (α) in terms of cylindrical coordinates z, r, and theta, resulting in a uniform percentage increase in height, width, and depth. On the other hand, anisotropic describes a non-constant thermal expansion coefficient, resulting in an uneven shape distortion when exposed to thermal energy. The isotropic or anisotropic tendency of a material is constant regardless of thermal quantity analysed, that is if a material has anisotropic expansion, it will also have anisotropic thermal conductivity due to differing structure characteristics[12]. However, if the material is non-homogenous, such as wood or marble, then it can be highly dependent on the sample tested and exhibit significant disparities.

Natural materials tend to be anisotropic, with Wood, Medium-density fibreboard, and Marble all found to have anisotropic expansion due to differing α values between the height and length (width) seen in appendix tables 4 and 5, a phenomenon in which aligns with preexisting thermodynamic theory. The diverging coefficients arise from differing crystallographic orientations within the material, specifically whereby grains of material are elongated or stretched in each direction[13]. As such, the experimental findings can be seen in table 2, whereby the coefficient differed between the height and length expansion, with the height expansion (in the z direction) coefficient be 10 times greater than that of length.

Wood and marble are therefore more responsive to thermal increases, and the extent at which atomic vibrations accumulate under these conditions is greater than those of ceramic and fibreboard. For both materials, due to their anisotropic nature, expansion for wood occurs to a larger extent on the transverse plane (normal to the grain)[7] and for marble it occurs along the grain.[14] Therefore, the magnetite and direction of thermal expansion is influenced by the specific shape and lattice preferred orientation of the material, which is not consistent across the general categories of wood and marble.[15] Resultingly, this tendency depends on the specific type or wood, or marble used and cannot be generalised as such. This increases stresses in some points, generating weak points which can undermine structural integrity. To account for and control this, this theory can be used to inform engineering decisions on where best to add structural support mechanisms when using these as building materials.

Alumina ceramic (Al_2O_3) on large scales is isotropic[16] due to the lattice composition of the compound, with the hexagonal packing and atomic structure facilitating the relatively equal expansion along all directions in a plane. On a molecular scale, individual grains may be considered anisotropic, however for most materials on a large scale these differences cancel each other out and the material is isotropic in bulk.[13] This is the case for construction and large-scale applications of ceramics. As such, the α found should theoretically be the same and the material isothermal, however this was not found in experimental investigation, with the calculated values differing significantly. This raises the potentially errors which existed in the experiment, impacting the validity and reliability of readings, overall reducing the accuracy. A uniform material is often desired as it follows theory for isotropic homogenous materials, making it easier to predict the response under changing thermal conditions. Resultingly, these materials are often used for high temperature situations due to the uniform temperature distribution minimising thermal stresses and optimising material lifespan.

4. Cooling

Analysis of the chronological cooling of materials using the thermal cameras allows for the visualisation and analysis of heat distribution over time. This is useful for the identification and analysis of the uniformity, or lack of, of the cooling of the material. Figure 3 (below) demonstrates this sequential cooling and photos at equal time intervals of each material cooling.

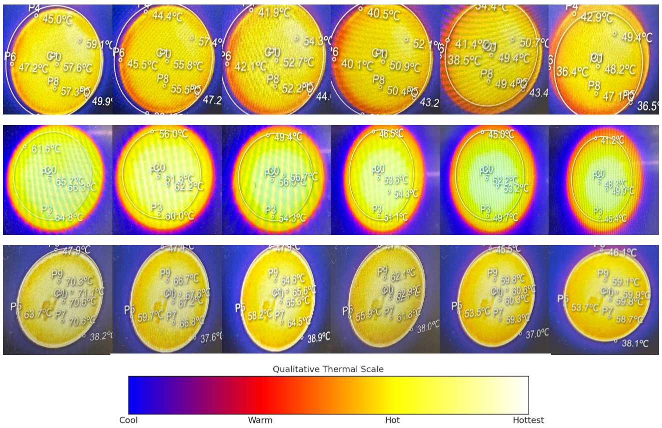


Figure 3: *Infrared images of cooling of plates of wood (row 1), ceramic (row 2) and marble (row 3) at regular time intervals of 1 minute from time = 0 to time = 5 with scale bar*

Figure 3 indicates that each material has an initial non-uniform distribution in the xy-plane. This is likely due to the slight variations in airflow patterns within the oven and non-uniform cooling during transportation from the oven to thermal camera. A possible resolution to this would be to increase the time that the materials were left in the oven. Irrespective of this, theoretically if the materials are isotropic (thus their conductivities are constant in every direction), their temperature should reach a radial distribution due to maximisation of entropy achievable in this radially symmetric configuration.[17] This is apparent for the ceramic in row 2 which shows that as time progresses the distribution (initially non-uniform) approaches a more radial distribution with the highest temperature in the middle which diffuses outwards by Fourier's law.

$$q = -k\nabla T.$$

Whilst often Fourier's law assumes symmetry in the radial direction around the midline, this is what is being analysed in this experiment thus the analysis is of 2D conduction in a non-steady state. This radial distribution characteristic of a uniform material is however not present in the wood and marble distributions which as seen in wood has an area in the top right corner across the whole-time evolution that is consistently hotter than the centre and in marble has a section in the bottom left that is consistently cooler than its surroundings.

If isotropic, this irregularity in the heat distribution should vary but due to its presence amongst the whole time series, it indicates the non-constant conduction coefficient of the materials and thus the anisotropic nature of the material and its cooling. This is expected of materials such as wood which are uniform often in the direction of the grain but non-uniform across the grain, an orthotropic material, symmetrical in 2 planes.[18] Furthermore, the nonuniformity of wood is due to natural growth patterns which can vary on the environment that the tree is grown making each piece of wood have a non-uniform distribution.

Marble is formed when calcite (limestone) is under high pressure and temperature in which the calcite crystals dissolve and reform to produce the much denser marble. In this recrystallisation, any impurities within the calcite can produce heterogeneities within the marble evident within marble's characteristic grains where the rock has a differing mineral composition and crystalline structure.[19] This results in the material not only being anisotropic but also non-homogenous and thus a non-uniform heat distribution indicating reasoning as to the deviation from the radial heat distribution. Just as wood has grain boundaries, so does marble and these barriers alter heat transfer due to the differing compositions between the two sides of the boundary and the associated conduction coefficients.[20]

The cooling of cork was not analysed due to its rapid cooling because of its small volume. This caused the cork to hold minimal thermal energy, and its rapid cooling saw no clear pattern emerge thus minimal analysis of the distribution of the heat could be performed. In examining the heat retention of these materials, over the course of 10 minutes, the marble lost an average of 19.55ºC and the ceramic lost 24.25ºC. The wood and cork which the experiments were run for 9 minutes due to time constraints showed an average loss of 14.75ºC and 22.55ºC respectively. All four materials showed a linear cooling trend as shown in figure 4 below.

Marble, wood and ceramic all showed strong linear relationships and were still in the process of cooling down however, the cork had less of a linear relationship. As observed in the experiment, cork was the smallest and thinnest material and had the largest change in temperature in the first minute. As can be seen in the graph, the cooling starts to slow as the temperature approaches room temp, creating a more characteristic cooling curve. This suggests that while cork quickly releases heat initially, it stabilises at a slower rate as it approaches ambient conditions. From these trends in figure 4 ceramic cooled the fastest followed by cork while marble and wood retaining heat better. In observing varying relationships, a common graph used in the regression of cooling data would be an exponential model. This was done as can be seen in figure 5.

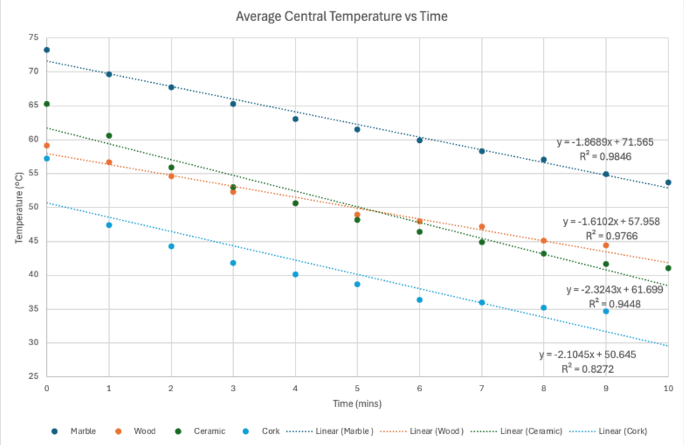


Figure 4*: Linear Regressions for cooling data*

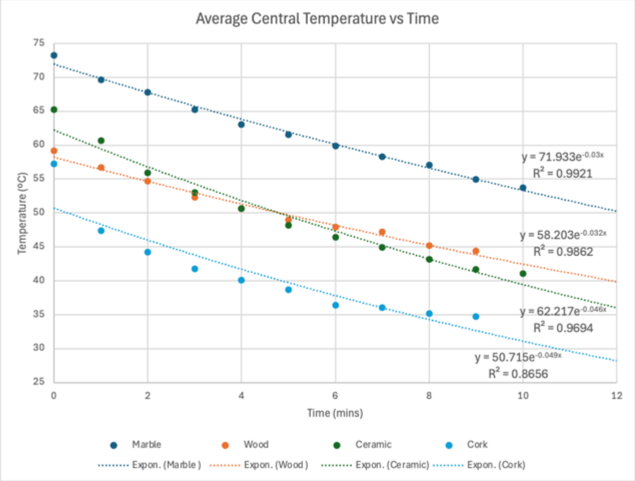


Figure 5*: Exponential Regressions for cooling data*

As can be observed in the R^2 values, the exponential regressions seem to fit the data better than the linear regressions, however the graphs still do not appear to be characteristic of a typical exponential cooling curve. This is because after 10 minutes had elapsed, the materials were still undergoing cooling and had not yet reached the recorded room temperature of 23ºC. If the experiment were to continue until room temperature was reached, it is likely the cooling curves would fit an exponential graph very well. Since the materials differed slightly in size and volume for a more accurate comparison, the values for rate of change of temperature over time per unit volume can be found in table 2 below.

Table 2: Cooling Rates

Material	*Raw sample volume (cm^3)*	*Rate of change per unit volume (℃/min cm^3)*
Wood	122.8	0.0131
Marble	86.7	0.0216
Ceramic	52.5	0.0443
Cork	26.1	0.0806

As seen in table 2, wood retains heat better than the other materials while cork retains heat the worst. Even though ceramic had the greatest temperature loss, when considering the volumes of each sample of material, the cork lost the fastest. This reflects how each material has varying thermal properties which are influenced by factors such as their surface area, density and specific heat capacity. For example, ceramic, despite having the greatest overall temperature loss, had a higher volumetric cooling rate, highlighting its lower thermal mass relative to its volume.

These findings can be applied to material selections in real world applications as they have practical implications where the ability to retain or dissipate heat is important in efficiency and performance. In construction, materials like wood are often favoured for interior structures and insulating elements due to its higher heat retention while ceramics are used where rapid cooling is needed such as in cooking surfaces and some heat exchangers. Likewise, cork's ability to cook quickly would be advantageous in applications that require effective insulation or a quicker temperature stabilisation. These fundamental thermal behaviours are important considerations for designing energy-efficient systems and selecting appropriate materials for specific thermal management needs.

4. Practical and Industrial Applications

Within construction, materials are often under high levels of tensile and sheer stress and thus must be able to handle these forces. On top of this, the natural cycle of the day as well as other factors such as the environment, geographical location, climate and proximity to heat sources such as furnaces exposes materials to different temperatures. Unequal distribution of heat within a material creates thermal stresses along the temperature gradient due to unequal thermal expansion.[21] In larger buildings, due to the larger load on the structure, it is essential to minimise the temperature gradient and distribute the heat in a uniform manner to decrease the thermal stresses on the materials.

As such, isotropy and homogeneity are often ideal cases as this allows for reliable predictions based on thermodynamic theory for homogenous materials whereby there is a uniform temperature gradient, and thus uniform thermal stress applied in all directions. For anisotropic materials, the thermal stress and structural fatigue must be correlated to the nonuniformity of the material, as such this makes it an unreliable construction material as these nonuniformities may vary between samples of materials due to an often lack of homogeneity. Due to expansion in different crystallographic direction and uneven atomic spacing, materials with both high thermal expansion coefficients and significant anisotropy are often unsuitable for usse in precision electrical applications, as dimensional changes can induce stress, misalignment, or changes in electrical performance due to geometry-dependent energy transfer limitations

Thermal cycling is often used to test thermal and structural integrity, determining the suitability of the given specimen for its intended purpose. The experimental procedure conducted one round of this cycling at a small temperature range; however, these tests can accumulate to 500 plus cycles. In industry these tests involve placing the material in oxygenated environments and exposing it to extreme thermal cycles of significantly high and low temperatures.[22] Furthermore, the effect of UV and air humidity can also be tested in similar stimulations[23] to give a comprehensive overview of the response of a given material. This intense testing procedure is vital in forming engineers of the durability, stability, bonding performance, and thermal responsiveness of differing materials. For anisotropic materials on a molecular level, each individual cycle creates microscopic damage at the grain boundary, and due to the anisotropic nature of many materials as well as their uneven grain distribution, some boundaries are more damaged than others. The extent of damage is directly proportional to the size of the temperature differences in the cycle, therefore more damage occurs on a seasonal basis as opposed to day to day.[24] Studies found that for marble, permanent expansion of certain types occurred by 0.2% (in volume) after exposure to 50 thermal cycles[24]

This is important to understand for marble as it is often used for historic restorations of art as well as small-scale construction within residential and commercial buildings. The diurnal heating of marble can cause large temperature differences in which literature indicates that these cycles can widen grain boundaries and produce sub-surface fractures due to the stresses induced in the non-symmetrical heat distribution reducing the structural integrity of the marble.[25] This suggests the minimisation of the usage of large slabs or marble that will have a large temperature gradient and elucidates the usage of thermal visualisation for historic marble sites to identify internal fractures and weak points within the stone's internal structure.

Wood's high thermal expansion and orthotropic properties are important considerations within its usage in construction. Its high thermal expansion which when used with other materials with varying thermal expansion coefficients can have the same effect of varying temperatures within a material as it produces areas of differing thermal expansions causing stress on the materials. The mismatching of thermal expansion coefficients is central to the warping, delamination and fractures of materials that can cause a severe decrease in structural integrity of materials and a core consideration within all applications where varying materials are used especially for high load bearing situations.[26] These results highlight the usage of expansion joints within construction that allow for this natural expansion[27] of the wood without incurring stress between pieces of wood by allowing for the natural expansion of the wood. Furthermore, the observed variations of temperature along grain boundaries (similar to the marble) indicate that for many purposes the wood grain must be aligned in order to minimise thermal stresses amongst the material.

Contrary to the wood and marble, ceramic's uniform heat distribution in the analysed plane due to its isotropic crystalline structure. This supports its usage in high temperature systems where its ability to evenly distribute temperature reduces the probability of crystal deformation and fissures forming in these situations such as kilns and electronics. For applications such as electronics where precision and repeatability are essential, the use of the ceramic's homogeneity is highly advantageous due to its predictability and explains their resurgence in the technological age.[28]

The low expansion of cork sees its use where gasket integrity is essential such as sealing wines where the possibility of intense cycles of expansion and contraction due to temperature fluctuations pose serious risks to the structural integrity of the glass especially as the bottle ages. Due to the small volume of the supplied cork and it being highly composed of air, the cooling phase was too fast for the time gaps, and it was difficult to observe any specific patterns within the cork however this may be quite advantageous as an insulator where air has a high thermal resistance to conduction and especially within a cultural shift towards more 'green' materials it may see the more widespread and frequency use of cork.[29]

5. Conclusion

The report analyses the heating up and associated thermal expansion as well as the cooling down due to convection and the associated distribution of heat in various materials. It was found that materials such as marble, wood and the cork (medium-density fibreboard) exhibited anisotropic expansion, a result of their natural origins causing their nanoscopic structures to be non-uniform. There was a significant deviation of the calculated thermal expansion coefficients between the experiment and literature which is likely due to the expansion of trapped water within the materials and it being the first time the materials are thermally cycled in which it is expected that these values deviate from literature. It is suggested that for future investigations, rather performing a single cycle, the materials are thermally cycled, and the thermal expansion is analysed per thermal cycle. Furthermore, it should be analysed if post heating and cooling the materials return to their initial volumes to see if the heating process caused plastic deformation and from this whether the trapped water had irreversible effects. During the cooling it was found that similarly to thermal expansion, the 'natural' materials had a non-uniform heat distribution due to their structural anisotropy where the ceramic, comprised of alumina, had a radial heat distribution due to its crystalline structure which is isotropic and homogeneity of material supporting its use in high-temperature applications requiring dimensional stability. It was found, which aligns with theory, that an exponential function fitting the cooling data the best compared to linear models. These insights are essential to material selection within real world applications such as construction and electronics.

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Appendix

Table 3: Dimensions of materials at room temperature (23(ºC/C)

	diameter (m)	*height (m)*	*volume (m^3)*
Marble	0.102	0.0107	8.67E-05
ceramic	0.104	0.00622	5.25E-05

wood	0.100	0.0155	0.
cork	0.0996	0.00335	2.

Table 4: Diameter of materials at (75ºC)

diameter (75 ºC) (mm)	*marble*	*ceramic*	*wood*	*cork*
1	0.127	0.129	0.125	0.124
2	0.128	0.129	0.126	0.124
3	0.128	0.129	0.126	0.124
4	0.126	0.129	0.125	0.125
Avg.:	0.127	0.129	0.125	0.124

Table 5: Height of materials at (75ºC)

Height (75 ºC) (mm)	*marble*	*ceramic*	*wood*	*cork*
1	0.0369	0.0318	0.0402	0.0286
2	0.0356	0.0321	0.0409	0.0287
3	0.0365	0.0316	0.0405	0.0286
4	0.0360	0.0320	0.0408	0.0287
Avg.:	0.0362	0.031	0.0406	0.0286

Table 6: Volume of materials at (75ºC)

Volume (75 ºC) (mm)	*marble*	*ceramic*	*wood*	*cork*
1	0.000471	0.000413	0.000491	0.000347
2	0.000456	0.000418	0.000510	0.000348
3	0.000468	0.000410	0.000503	0.000347
4	0.000450	0.000417	0.000503	0.000349
Avg.:	0.000461	0.000414	0.000502	0.000348

Example calculation for marble sample at 75ºC:

$$V = \pi r^2 h$$

$$V = \pi\left(\frac{0.127}{2}\right)^2 0.0369 = 0.00471 m^3$$

Table 7: Experimental thermal expansion coefficient calculation

Material	*Initial length*	*Final Length*	*Temperature Change*	*Linear thermal expansion coefficient*
	m	*m*	*ºC*	*ºC^{-1}*
Marble	0.102	0.127	52	0.00486
ceramic	0.104	0.129	52	0.00465
wood	0.100	0.125	52	0.00483
cork	0.0996	0.124	52	0.00478

Example calculation for marble:

$$\alpha = \frac{\Delta L}{L_{initial} \times \Delta T}$$

$$= \frac{0.127-0.102}{0.102\times(75-23)} = 0.00486/ ºC$$