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THERMAL CONDUCTIVITY OF TROPICAL WOOD : INFLUENCE OF MOISTURE, CUTTING LEVEL AND PRINCIPAL CUTTING PLAN.

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ABSTRACT

The authors carried out a research on heat conductivity of five species of tropical wood, covering the range of densities corresponding to most woods used in building (framing and heavy construction work, window framing, fencing, interior joinery and veneers) in Cameroon namely Tali (*Erythrophleum ivorense*) and Bilinga (*Nauclea diderrichii*) with an average density of 900 kg/m3, Sapelli (*Entandrophragma cylindricium*) and Sipo (*Entandrophragma utile*) with a density of 600-700 kg/m3, Ayous (*Triplochiton scleroxylon*) with a density of 400 kg/m3 , all densities given for a moisture content of 15%.

Aware of the fact that wood is not homogeneous, the tested samples are identified from the cutting level (bottom, middle or top of the trunk) and the principal cutting plan (longitudinal, tangential and radial). The experimental technique is the "methode des boites" which is a steady state method developped in the LETS -Lyon. Over 350 measurements have been performed.

Thermal conductivities and densities increase in almost a linear way with moisture content. The cutting level has a marked influence on the density and a weaker influence on the thermal conductivity. For a given species and a given cutting level, the difference between tangential and radial conductivities is unobservable.

To be able to predict thermal conductivities of wet woods (above the Fiber Saturation Point), physical models are presented both for transverse and longitudinal directions. The models are relevant with respect to the experimental data. It is shown that for most specimen constant values of the conductivities of the cell walls are consistant with the experimental results ($0.85\ Wm^{-1}K^{-1}$ for longitudinal conductivity, $0.53\ Wm^{-1}K^{-1}$ for transverse conductivity).

Experiments on the conductivity of tropical woods have been led by Maku [1], Wangaard [2], MacLean [3] over a wide range of species (softwoods and hardwoods) especially from temperate countries, with relatively low densities and low moisture contents. The experimental work that is presented herein deals with five species which are representative of the Cameroonian market, namely Tali (*Erythrophleum ivorense*) and Bilinga (*Nauclea diderrichii*) with an average density of 900 kg/m3, Sapelli (*Entandrophragma cylindricium*) and Sipo (*Entandrophragma utile*) with a density of 600-700 kg/m3, Ayous (*Triplochiton scleroxylon*) with a density of 400 kg/m3 , all densities given for a moisture content of 15%.

EXPERIMENTAL PROCEDURE AND RESULTS

Samples were taken from the top of the tree (H), from the middle (M) or from the base (B). All trees were cut down from a secondary forest about a hundred kilometers far from Yaounde (Cameroon). For a given level (B, M or H), test specimens were cut (fig. 1) according to the three principal plans defined for wood (tangential t, radial r, and longitudinal L). The following designation was adopted : BiHt means for instance a test specimen of Bilinga taken from the top of the tree, the heat flow being tangential. The typical specimen size is 27 cm x 27 cm with a thickness ranging from 3 to 5 cm.

The experimental apparatus (fig. 2) has been thoroughly described by Ngohe-Ekam [4]. One face of the specimen is covered with an insulated box. On the top of the box, a heating element warms the air-gap in contact with the specimen. The other face is in contact with an air space cooled by a heat exchanger fed by a mixture of water and glycol. Temperature sensors are placed on both faces of the specimen as well as in the different air spaces. No guard ring is set, but the heat losses are evaluated between the warm box and the environment. The method ("méthode des boîtes") has shown to be precise and effective for large and poorly conducting samples, especially building materials [5]. The average temperature of the sample ranges between 14° and 20°C. The moisture content ranges from 5% to almost saturation.

For each specimen, the thermal conductivities and densities are measured for different moisture contents (Fig. 3-4 for SaBt, SaMt and SaHt). Over 350 measures of λ and ρ were obtained. The forms of the curves suggest linear correlations. The curves are fitted to the data by the method of least squares and the correlation index are in all cases excellent (Table 1). In fact, for low moisture contents, the variation of λ and ρ with moisture is weak. Above Fiber Saturation Point (FSP), the linear variation is more pronounced.

INFLUENCE OF CUTTING LEVEL AND CUTTING PLAN

For a given specimen and a given moisture content, the analysis of cutting levesl shows that the samples taken from the medium level have lower densities (Figure 3.) than samples taken from the base or the top. This can be explained by the fact that fibers are reinforced near the roots and the branches. This conclusion was established for all specimen. For thermal conductivities, the tendancy is not clearly marked since thermal conductivity of the wall cells may vary from a specimen to another. It can be seen on Figure 4. that SaMt has a lower density and a higher thermal conductivity than SaHt and SaBt.

There are no significant difference between tangential and radial conductivities which are of the same order of magnitude. A few specimens present anomalies (AyBr and AyHr with unusually high conductivities and SiML with an unusually low conductivity) and are not taken into account in the next section.

THERMAL CONDUCTIVITY MODELS ABOVE THE FIBER SATURATION POINT

Models for dry-wood heat conductivities have been proposed by several authors (Hart [9], Siau [6], Maku [1]). These models have a direct application in building, window framing, interior joinery and veneer. For wet-wood (above FSP), MacLean [3] has established an empirical formula for a great number of species (see below).

Physical models based on the thermal properties of the different constituents of wood are proposed hereafter for transverse and longitudinal heat transfer in wet woods. These models are compared with the experimental results on the five studied species.

Transverse conductivity

The *transverse conductivity* λ_T refers to the thermal conductivity in the radial and the tangential directions.

According to a formula established by Siau [6], the air fraction ε_a is derived from the expression :

$$\varepsilon_a = 1 - \frac{\rho}{\rho_w}\frac{M/100 + 1000/\rho_p}{M/100+1} \qquad (1)$$

Where ρ is the measured density of wood ($kg/m3$) at moisture content $M(\%)$, $\rho_w = 1000\ kg/m^3$ is the density of water, ρ_p is the density of the cell wall substance. An average value of $\rho_p = 1500\ kg/m^3$ discussed by Siau [6] is used in this section.

Little experimental studies for high density and high moisture contents are available. So far, MacLean [3] has established an empirical formula for $M \geq 40\%$, mainly for medium-weight woods:

$$\lambda_T = [2.38\varepsilon_a + \frac{\rho}{\rho_w}\frac{0.548M/100+21.68}{M/100+1}] X\ 10^{-2} \qquad (2)$$

Above FSP ($M \geq M_{FSP}$), let us consider wood as a *wet matrix composed of cell wall, bound and free water* with thermal conductivity λ_{mT} and air with thermal conductivity λ_a trapped in cylindrical cells distributed randomly in the matrix. According to Hashin [7], the equivalent thermal conductivity of this 2D composite structure (Hashin Upper Bound) may be evaluated by :

$$\lambda_T = \lambda_{mT} + \frac{\varepsilon_a}{\frac{1}{\lambda_a - \lambda_{mT}} + \frac{1-\varepsilon_a}{2\lambda_{mT}}}, \qquad (3)$$

thus introducing the variable:

$$p = (\lambda_{mT} - \lambda_a)/\lambda_{mT} + \lambda_a), \qquad (4)$$

Equation (3) can be reduced to :

$$\lambda_T = \lambda_{mT}\frac{1-p\varepsilon_a}{1+p\varepsilon_a} \qquad (5).$$

With the value of $\lambda_a = 0.024\ Wm^{-1}K^{-1}$, $\lambda_{pT} = 0.46\ Wm^{-}K^{-1}$ (Thermal conductivity of cell wall in transverse direction) and $\lambda_w = 0.595\ Wm^{-1}K^{-1}$ (Thermal conductivity of free water), an average value of $\lambda_{mT} = (\lambda_{pT} + \lambda_w)/2 = 0.53\ Wm^{-1}K^{-1}$ is retained.

Experimental data for ρ are used together with Equation (1) to calculate ε_a. The relationship between λ and ε_a for all the specimens, is depicted in Figure 5. Results from Equation (5) are superposed to the experimental data. It can be seen that this equation gives a good average value of λ especially for $0 \leq \varepsilon_a \leq 0.3$. This result may be explained by the fact that Equation (3) applies for rather low values of ε_a thus to medium-weight or heavy woods.

A more reliable estimate of λ_{mT} can be obtained, taking into account the volume fraction of free water ε_w and the volume fraction of bound water and wall cell ε_p. A simple parallel arrangement leads to the following expression :

$$\lambda_{mT} = \frac{\varepsilon_p \lambda_{pT} + \varepsilon_w \lambda_w}{\varepsilon_p + \varepsilon_w} \qquad (6)$$

where

$$\varepsilon_p + \varepsilon_w + \varepsilon_a = 1 \qquad (7)$$

The value of ε_p can be obtained at FSP; ε_{aFSP} is obtained from Equation (1) with $M = M_{FSP}$. The value of M_{FSP} depends on the wood, but for M ranging from 20% to 40%, there is little influence on the calculated value of λ_T. The values chosen in Equation (1) are $M=30\%$ and $\rho(M=30\%)$ extrapolated from Table 1.

For $M \geq 30$: $\varepsilon_p = 1 - \varepsilon_{aFSP}$ (8)

From Equation (6) : $\varepsilon_w = 1 - \varepsilon_a - \varepsilon_p = \varepsilon_{aFSP} - \varepsilon_a$ (9)

Combining Equations (1), (5), (6), (8) and (9) with the experimental data, the value of λ_{pT} has been adjusted to fit the experimental data for transverse heat conductivity. As depicted in Table 1, for most specimens (BiBt, BiMt, BiHt, SaBt, SaHt, TaBt, SiMt, SiHt, BiBr, BiMr, BiHr, SaBr, SaHr, TaBr), an average value of λ_{pT} **is** $\boldsymbol{0.53 Wm^{-1}K^{-1}}$. The difference between radial and tangential is weak and would not lead to a clear interpretation. The value of λ_{pT} is higher than the value recommended by Siau : $\lambda_{pT}=0.46\ Wm^{-1}K^{-1}$ but one must keep in mind that the latter was established for dry woods. On Figure 6, a comparison between this model and experimental results is shown. The model is also compared to MacLean's empirical formula (Eq.(2)).

For a few specimens, the adjustment gives a higher or a lower fitted conductivity of the wall cell (Table 1). One explanation is given by Wangaard [2]: thermal conductivity of cell wall is connected to the fibril angle i.e the angle of the polysaccharide chains with the longitudinal axis. This angle is affected by the chemical composition of the wood cell. In particular, compression wood presents a higher percentage of lignin and a higher fibril angle thus a higher transverse conductivity.

Longitudinal conductivity

As mentionned by several authors (Siau [6], Kollmann and Malmquist [8]), a parallel arrangement conveniently describes the thermal behaviour of wood fibers in the longitudinal direction :

$$\lambda_L = (1-\varepsilon_a)\,\lambda_{mL} + \varepsilon_a\,\lambda_a = (1-\varepsilon_a)\,\lambda_{mL} \qquad (10)$$

using an average value for the conductivity λ_{mL} of the matrix (cell walls and bound water) in the longitudinal direction. Figure 7 shows for the five studied species that a correct fitting is possible with $\lambda_{mL}= 0{,}80 Wm^{-}K^{-1}$.

For a better precision, the expression of λ_{mL} can be detailed, thus giving the following equation:

$$\lambda_L = \varepsilon_p\,\lambda_{pL} + \varepsilon_w\,\lambda_w + \varepsilon_a\,\lambda_a \qquad (11)$$

where λ_{pL} is the thermal conductivity of cell walls in the longitudinal direction. As in the previous section, the different porosities are obtained from Equations (1), (8) and (9). The fitted values of λ_{pL} for each specimen tested are given in Table 1. The average value ($\boldsymbol{\lambda_{pL} = 0{,}85 Wm^{-1}K^{-1}}$) is close to the one proposed by Siau ($\lambda_{pL}= 0{,}88 Wm^{-1}K^{-1}$). On Figure 8 are shown comparisons between some experimental data and the proposed model.

CONCLUSION

Over 350 measures of thermal conductivities for tropical woods have been done at different moisture contents, in different directions and at different cutting level. Models for the heat conductivity of wood above FSP have been successfully used to fit the experimental results. Whereas a simple parallel model is enough for longitudinal heat transfer, a statistical model describing air as cylinders randomly distributed in a matrix of fibers and water was used to obtain transverse heat transfer. These models have permitted to affect values to the heat conductivities of water saturated cell walls in both directions.

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Table 1 : Values of the coefficients for the linear regressions :
$\rho=aM+b$; $\lambda=(cM+d)X10^{-2}$; r is the correlation index;
Values of adjusted wall cell conductivities :
λ_{pT} is adjusted from Eq. 6; λ_{pL} is adjusted from Eq. 11.

		a	b	r	c	d	r	λ_{pT} or λ_{pL}	
TANGENTIAL	AyHt	3.24	355.0	0.99	1.37	122.9	0.98	0.65	λ_{pT}
	BiBt	5.79	788.5	0.98	3.85	184,4.	0.98	0.50	
	BiMt	5.55	701.9	0.99	3.37	182.9	0.98	0.50	
	BiHt	5.85	764.5	0.98	4.28	204.8	0.99	0.55	
	SaBt	4.10	644.1	0.99	2.54	153.3	0.99	0.50	
	SaMt	5.00	536.8	0.99	2.72	170.4	0.99	0.62	
	SaHt	4.33	678.6	0.98	1.98	192.7	0.94	0.50	
	SiBt	3.95	551.5	0.98	1.24	148.8	0.98	0.40	
	SiMt	3.72	513.0	0.99	2.67	86.8	0.97	0.50	
	SiHt	4.05	652.6	0.97	3.05	110.2	0.97	0.42	
	TaBt	5.42	871.2	0.99	3.92	206.6	0.94	0.50	
RADIAL	AyBr	3.29	340.3	0.99	2.01	116.7	0.98	0.80	λ_{pT}
	AyHr	3.39	374.7	0.99	1.33	141.2	0.98	0.80	
	BiBr	5.18	704.9	0.98	3.52	184.0	0.95	0.55	
	BiMr	5.43	742.0	0.99	4.03	184.6	0.97	0.55	
	BiHr	5.94	758.6	0.99	4.78	180.2	0.99	0.55	
	SaBr	4.32	610.1	0.99	2.66	168.6	0.98	0.57	
	SaHr	4.34	629.4	0.99	2.92	154.6	0.98	0.57	
	TaBr	5.94	870.6	0.99	4.17	213.3	0.97	0.50	
LONGITUDINAL	AyBL	3.20	340.3	0.99	1.66	268.8	0.97	0.86	λ_{pL}
	AyHL	3.37	381.6	0.99	2.00	259.5	0.98	0.86	
	BiHL	5.89	775.2	0.99	4;28	437.7	0.99	0.84	
	SaBL	5.22	601.2	0.99	2.87	354.9	0.96	0.90	
	SaML	4.74	557.1	0.99	3.44	361.7	0.99	0.90	
	SaHL	4.42	716.8	0.98	3.05	427.6	0.94	0.83	
	SiBL	3.24	584.8	0.98	2.99	352.2	0.98	0.85	
	SiML	3.79	484.9	0.99	1.65	156.5	0.97	0.40	
	SiHL	4.52	544.6	0.99	2.48	313.7	0.97	0.75	
	TaBL	5.66	876.4	0.97	4.72	527.7	0.94	0.85	

Figure 1. : Description of a specimen by its position in the trunk (H, M, B) and the direction of the heat flux (l, r, t)

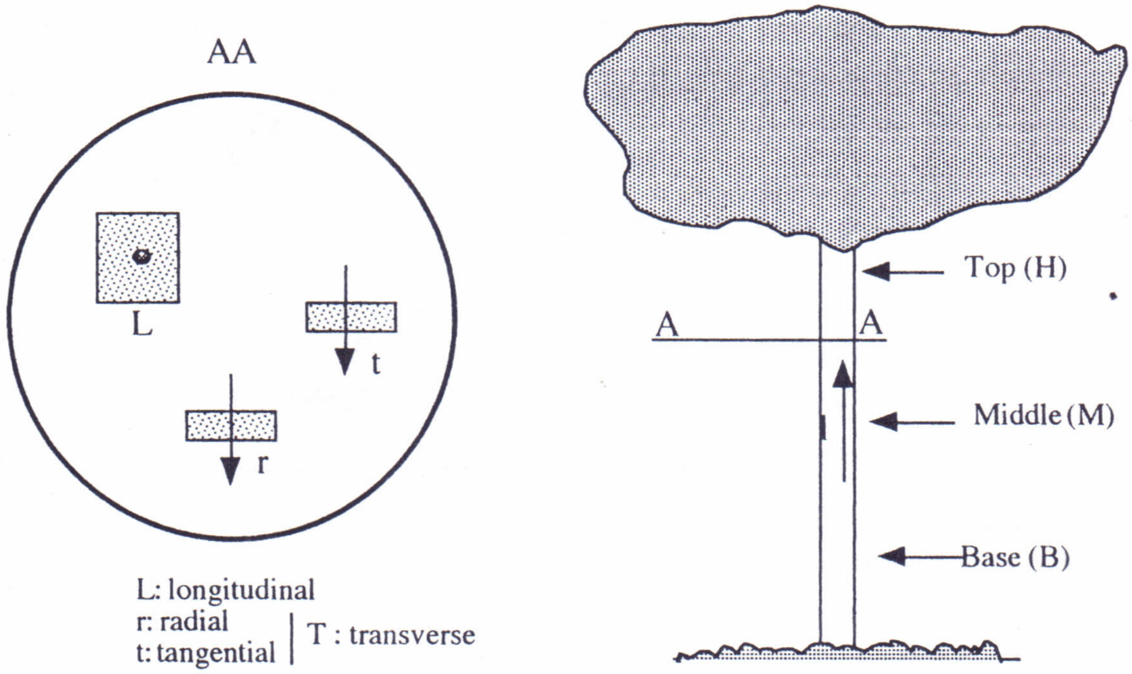
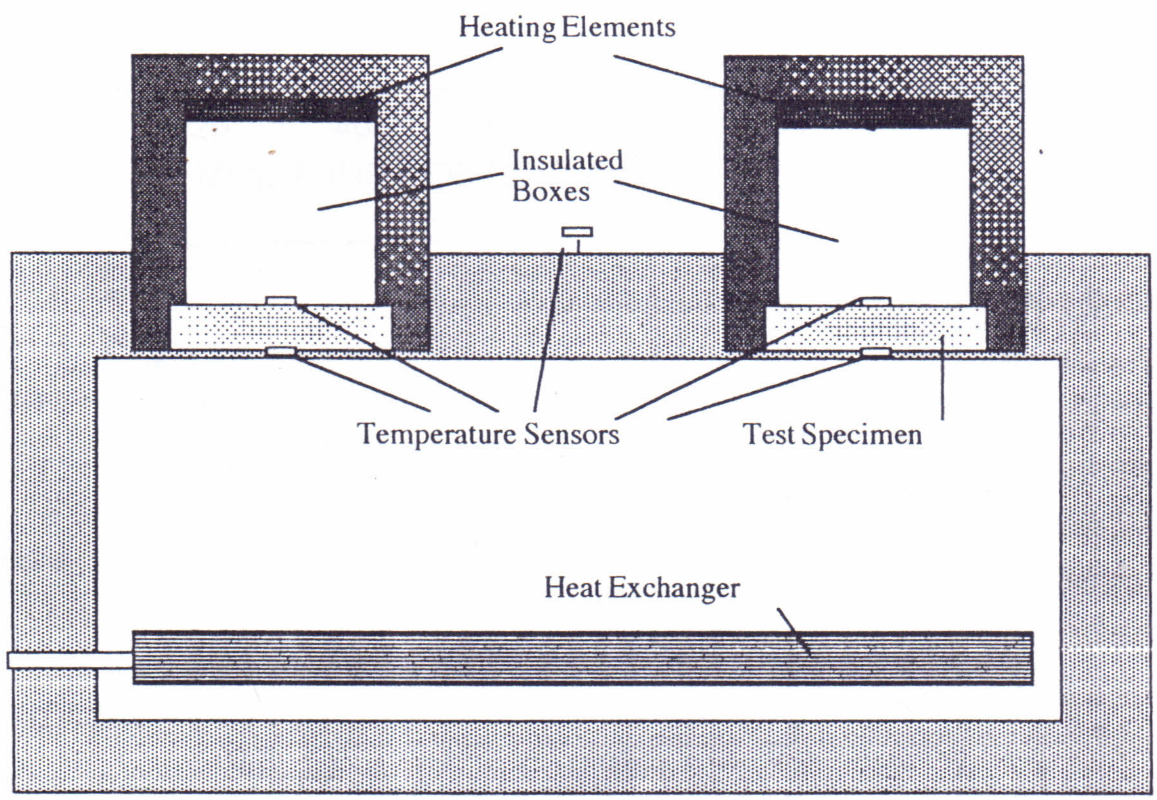


Figure 2. : Section View of the Experimental Apparatus



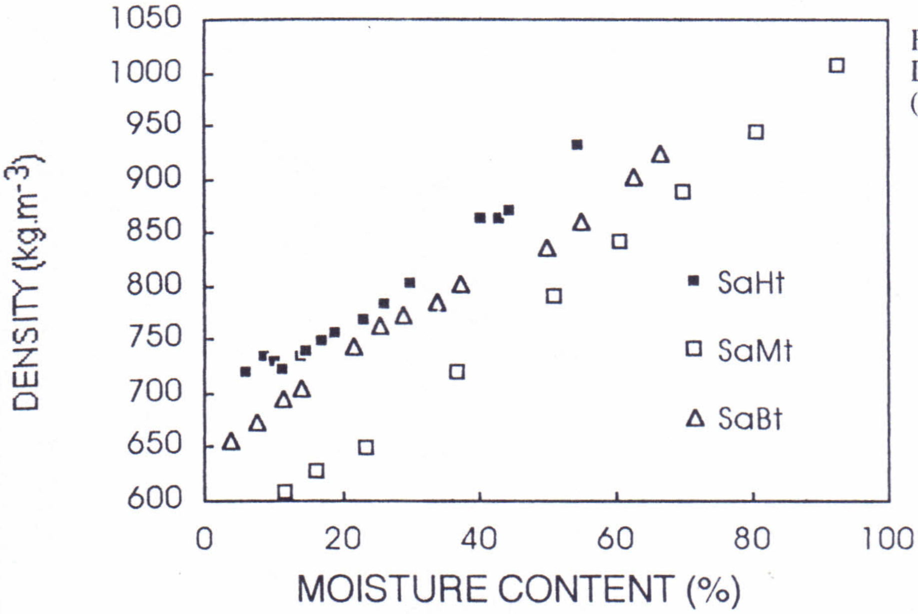


Figure 3 :
Density vs. moisture content (Sapelli)

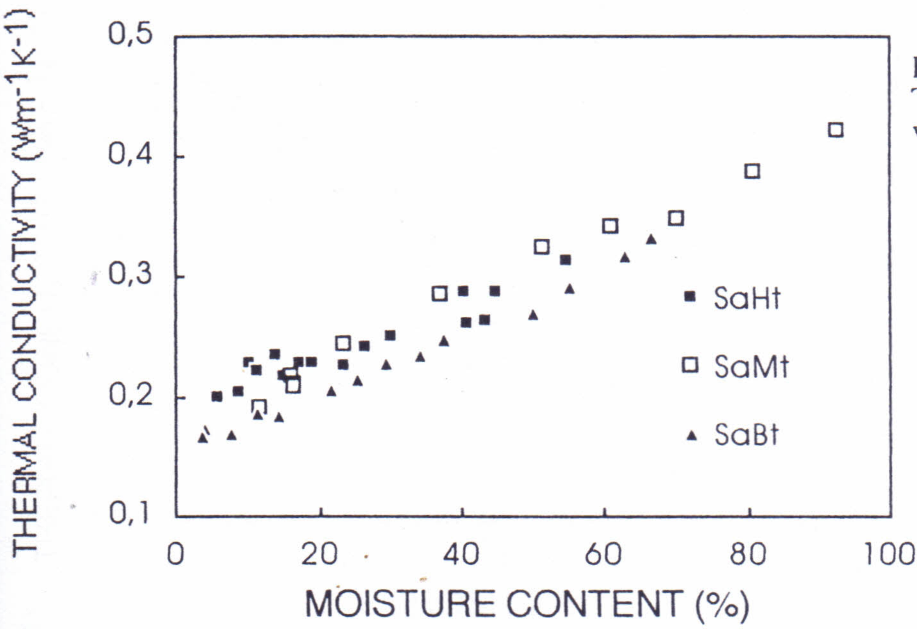


Figure 4 :
Tangential conductivity vs. moisture content (Sapelli)

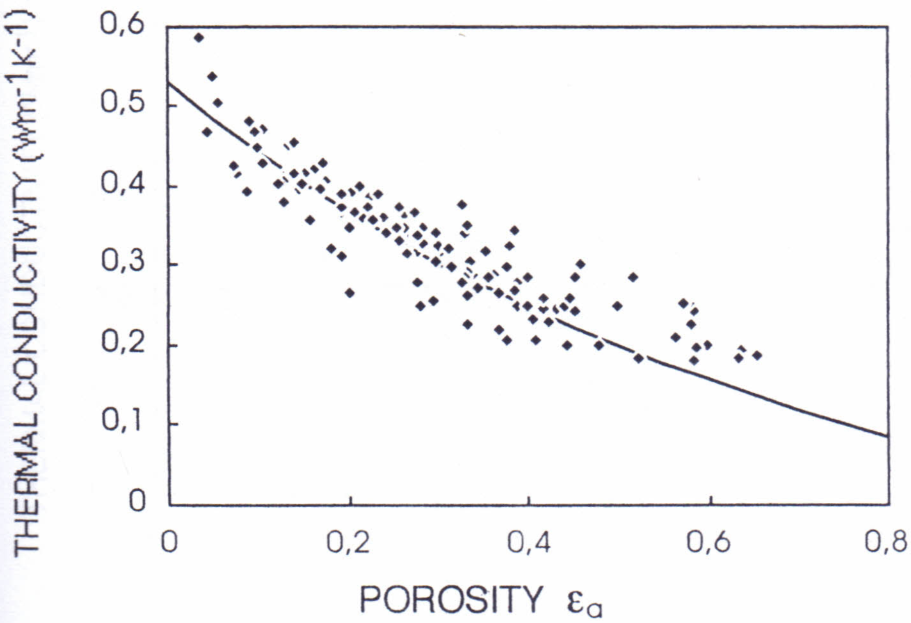


Figure 5 :
Transverse conductivity vs. porosity above FSP
◆ Experimental
—— Equation (5) with
λ_{mT}= 0.53 $Wm^{-1}K^{-1}$
λ_a= 0.024 $Wm^{-1}K^{-1}$

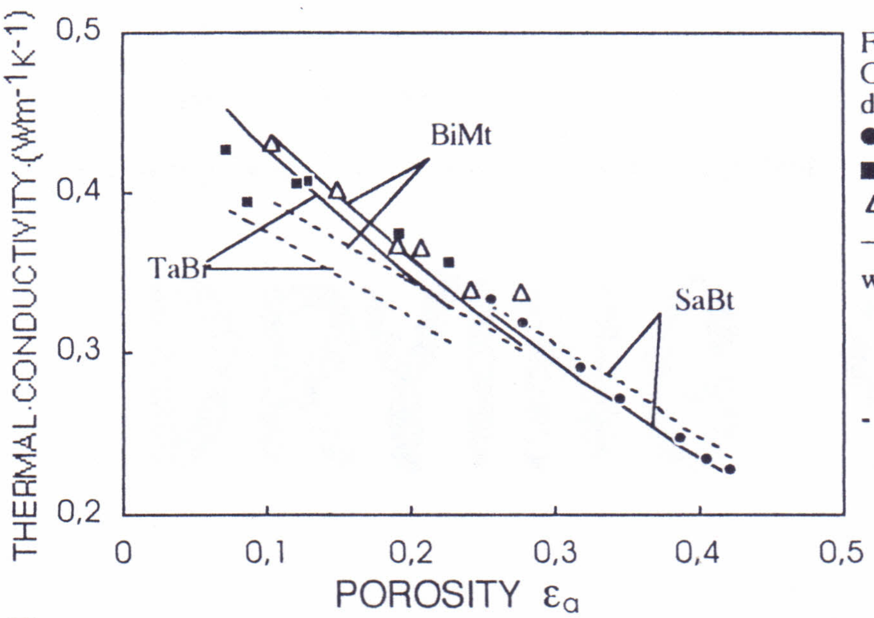


Figure 6 :
Comparison between experimental data and models:
● Experimental : SaBt
■ Experimental : TaBr
Δ Experimental : BiMt
—— Present Model (Eq. 5 and 6.)
with $\lambda_{pT}= 0.50\ Wm^{-1}K^{-1}$
$\lambda_a= 0.024\ Wm^{-1}K^{-1}$
$\lambda_w= 0.595\ Wm^{-1}K^{-1}$
- - - - Mac Lean (Eq. 2)

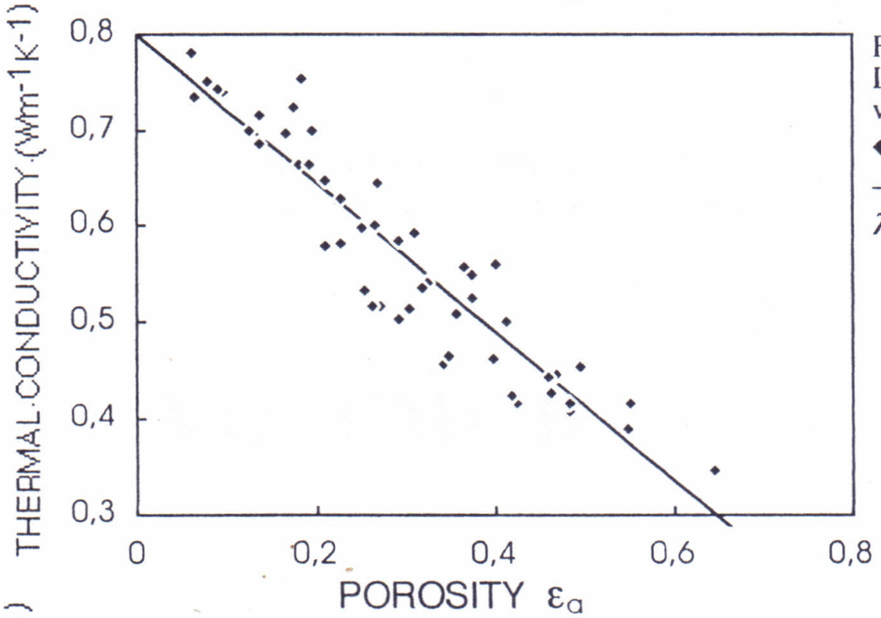


Figure 7 :
Longitudinal conductivity vs. porosity above FSP
◆ Experimental
—— Equation (10) with
$\lambda_{mL}= 0.80\ Wm^{-1}K^{-1}$

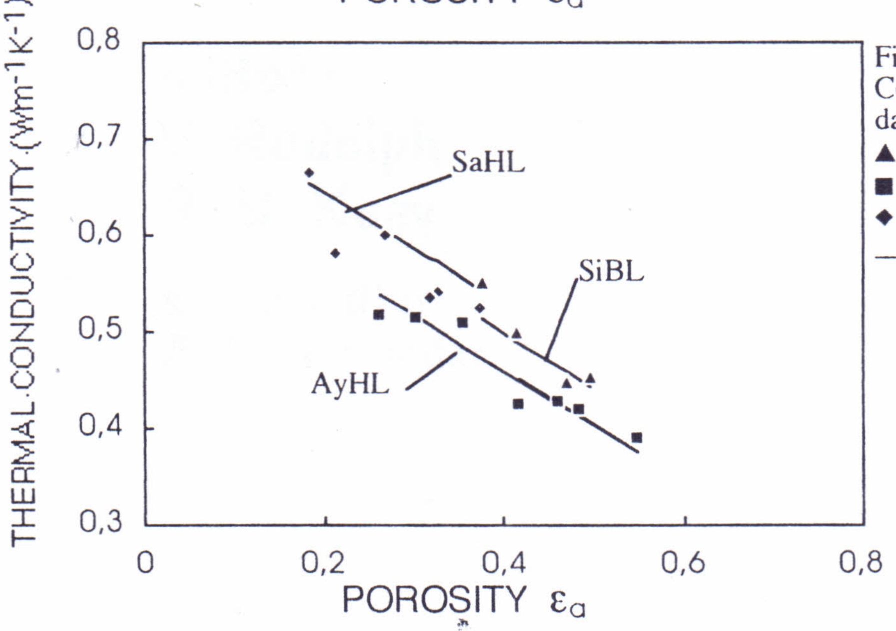


Figure 8 :
Comparison between experimental data and models:
▲ Experimental : SiBL
■ Experimental : AyHL
◆ Experimental : SaHL
—— Present Model (Eq. 11.) with
$\lambda_{pL}= 0.85\ Wm^{-1}K^{-1}$
$\lambda_a= 0.024\ Wm^{-1}K^{-1}$
$\lambda_w= 0.595\ Wm^{-1}K^{-1}$

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