J. Rech. Sci. Univ. Lomé (Togo), 2012, Série E, 14(1) : 11-20

A NOVEL METHOD OF DENSITY DETERMINATION FOR WATERLOGGED WOODS: COMPARISON WITH A KNOWN CLASSICAL TECHNIQUE

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(Reçu le 22 Septembre 2011 ; Révisé le 06 Mars 2012 ; Accepté le 24 Mars 2012)

ABSTRACT

In the course of research for conservation treatments of the waterlogged woods archaeological artefacts, characterisation of degree of woods decay seemed to be a major step in choosing of feeler concentrations for structural consolidation. For purpose, the Maximum Water Content (MWC) and density were the common parameters used for determining degree of the waterlogged woods degradation. As for fresh wood, assessment to the real density of waterlogged woods (R_{GR}) was fastidious. Then, the conditional density (R_{GC}) of wood was always determined on basis of Smith relation. The latter was subjected to an established hypothesis that stipulates a constant value for density of wood dry-matter of about 1.5.
The actual paper proposes a novel method for determination of waterlogged wood conditional density. It's fundamentally based on Archimede principle, as those kinds of woods were completely watering submersible. The obtained results have been compared with those from application of the modified Smith formula. A good correlation was reached between the two methods. It immediately followed that assumption of constant density of fresh wood dry-matter (value 1.5), drove to a good approximation in usage of Smith formula. However, this approximation did not still hold for slightly degraded woods as shown by compared results of these two methods. The main advantage of the proposed method linked with its practical measurements in real conditions
and the fact that no assumption for the wood cell wall density was necessary.

Key words: Wood, waterlogged, conditional density, maximum water content.

RÉSUMÉ

Dans les recherches relatives aux traitements dédiés à la conservation des objets archéologiques en bois gorgés d'eau, la caractérisation du degré de dégradation du bois constitue une importante étape dans le choix des concentrations du matériau d'imprégnation - consolidation. La teneur maximale en eau et la densité sont couramment utilisées pour évaluer l'état de dégradation du bois. L'accès à la densité réelle d'un bois gorgé d'eau (R_{GR}) est ardu. La densité conditionnelle (R_{GC}), déterminée à partir de la relation de Smith modifiée, a donc été admise quand bien même elle reste sujette à l'hypothèse de la constance de densité de la matière sèche du bois.
Le présent article propose une nouvelle méthode de détermination de la densité des bois gorgés d'eau. Elle est fondamentalement basée sur le principe d'Archimède et tient pratiquement au fait que ces types de bois sont complètement submersibles dans l'eau. Les résultats obtenus, comparés à ceux déterminés par la formule classique de Smith, ont montré une bonne corrélation entre les deux méthodes. Il s'en suit immédiatement que, l'hypothèse sur la densité de matière sèche du bois frais (1,5) est bien confirmée. Toutefois, l'approximation ainsi faite ne tient plus pour les bois peu dégradés. Les avantages de la nouvelle méthode sont essentiellement liés au fait qu'elle s'appuie sur des mesures pratiques en conditions réelles et qu'aucune hypothèse, sur la valeur de la densité de la substance de la paroi cellulaire, ne soit nécessaire pour son application.

Mots clés: Bois, gorgé d'eau, densité conditionnelle, teneur maximale en eau.

I- INTRODUCTION

The waterlogged woods were those belonging to ancient boats or shipwrecks and any wooden artifacts that stayed for long time under the watering conditions. They were characterized by higher water absorption as consequence of some structural material losses [1-8]. The degree of degradation must be taken into account when selecting the impregnation material concentrations [6]. Chemical analysis, moisture content, conditional density and microscopy analysis were often suggested for purpose of wood decay determination [3-8]. Chemical analysis was useful for knowledge of degree of wood deterioration [6]. Moreover, as it has been stated, it required at means 20g of wood sample, consumed long time and was expensive. Chemical analysis realization is highly fastidious and could not then be done for all of the waterlogged wooden artifacts to be treated [6-7]. The chemical analysis of woods alone has been recognized as not sufficient for characterizing decay status of the waterlogged wood [8]. Moisture content, calculated in form of the maximum water content, and density of woods coupled with microscopy screening were the common means for waterlogged woods characterrization [3; 8]. Specific gravity of wood was a good indicator for evaluating degree of the wood degradation [9]. Maximum water content could be easily linked with the conditional density of wood if admitting hypothesis on constant density for dry substance of wood [3; 9-10].

An original suggestion in literature for determination of wood density was due to Smith [12]. The author showed that the specific gravity of a wood sample could be estimated using relation (2). This was well adapted for highly decayed waterlogged woods but less deteriorated woods might sometimes under/over estimated [1]. The proposed method for density evaluation for the waterlogged woods consisted first, on the application of Archimedes principle for reaching its apparent density. Secondly, a correction was applied to account for the quantity of water that engorged and supersaturated the decay wood fibers. Maximum moisture content of wood was then chosen as the correcting factor. The obtained results showed that, the novel method was a powerful means for determining the density of waterlogged woods. Density values fairly well correlated with the calculated R_{GC} according to Smith modified relation. The validity for recognition of Smith relation was subject to assumption of constant density for dry-matter of wood. As shown in this proposed new method, it's no longer necessary to make such assumption. The procedure might also be extended to kinds of moist products, free of gases, as some fresh tubers which are completely water submersible.

II- MATERIALS AND METHOD

2-1- MATERIALS

Experimental wood materials originated from the same various waterlogged woods to which were applied the design treatments for conservation. They came from different wood species and have been supplied by either Centre Camille Julian from CNRS of Marseille (France), or Centra Arqueologia Subaquatica Cataluña of Girona (Spain) and Centro Restauri Gallo (Italy). Identification tests make known that the wood samples, from Marseille, were from Dramont and Cavalière shipwrecks. The former consisted mainly of pinus *leucodermis* species while parts of the latter belonged to Quercus, albies alba and pinus (halenpensis, pinea, maritima, sylvestris) species. Most of the other investigated waterlogged woods species were unidentified. It's the reason why the wood samples in the current work were just encoded as S_n (n = 1, . . , 41): thus from S_1 to S_{41}.

For mass determination, a $1/100^{th}$ mettler SARTHORIUS SB1600 was used. Deionised (desalting or distilled) water and 250mL glass-beaker (1mL divisions) were required for measurements of displaced volume of water by the insert wood sample.

2-2-PROCEDURE

The samples of waterlogged woods were cut into geometrical regular forms for facility of their dimensions measurement. Rectangular or cubic wood samples were the simplest forms to adopt and their sizes must be such that each sample could be inserted into the glass beaker without any difficulty. Fur purpose, it can be indicated that 250mL SIMAX glass beaker has 35mm inner diameter. Samples of about 15x15x20mm dimensions are useful for these performed experiments. In the sampling procedure, wood samples are previously rinsed with ordinary water and stored in ionised or desalting water for at least two days before measurements take place.

Determination of the apparent density is accomplished by following eight (08) steps of the described procedure hereafter:

1- The glass beaker was cleaned with ionized water at the beginning and air-dried.

2- The beaker is then weighed free. Suppose that (W_B) is its mass when free.

3- The ionized water is introduced in the beaker until a set graduation is reached using a pipette system. This system permits to avoid repellent of water droplets on the free part of the beaker wall. The set volume value (V_{Wi}) may be respected for all the measurements for data accuracy, if comparison among various kinds of woods is necessary. We have retained 150mL as the setting value V_{Wi} in all our experiments.

4- We then read and note the mass (W_W +W_B) of beaker filled with ionized water.

5- We weigh thereafter an already prepared wood sample alone and note its mass value (S_W). This sample has been measured for radial x tangential x axial dimensions. The recorded values allow for calculation of samples volume, on their dimensions basis. They can also serve for identifying eventual errors in determination of the displaced water volumes. We have shown that both these two different measured volumes are of the same order when convenient reading precaution and verification are taken in the course of the trials.

6- We therefore introduce the wood sample in the water filled beaker. Care is taken, by slightly inclining the beaker, to avoid the water loss by repellence on the non-wetting part of beaker. Then, the water-beaker-wood sample mass (W_W +W_B+W_S) and the total volume (V_{Wf}) are read and recorded for calculations.
These previous monitored data can already allow for determination of the apparent density of wood sample by simple calculations. However, we think that it's preferable to have a direct access to the conditional density of wood at once. Before this can be done, all of the needed parameters should be totally determined for each of the wood species. It's the reason why the following last procedure step is necessary.

7- In parallel with apparent density measurement, determination of the moisture content is performed on small cut samples from the same waterlogged woods. It serves in procedure for correction because the measured apparent density comprises the water that had logged this kind of wood. For this purpose, the wood moisture content, expressed in dry basis (equal to Maximum Water Content), is chosen as the correcting factor. As the mass of waterlogged wood sample is the sum of remained dry-matter mass and that of contain water.

The moisture content of wood samples has been determined using a hot air drying oven running at 105°C for more than 10 hours. It's confirmed with an infrared desiccator - Mettler at 140°C, each measurement taken between 35 to 50 min, although the infrared mean is not yet normalised. Experimental samples for the moisture analysis consist of small cut wood samples of about 2g. The sample mass is chosen as reference because it is difficult to cut regular form of the too small cubic samples of 1-cm dimension without a great loss of wood material. This value is thought to be sufficient but can vary according to availability of the raw material. However, the set value must be respected as possible between two consecutive measurements for the same wood specie. Too small samples may falsely give high value for moisture content compared with relatively big samples from the same wood section.

8- The conditional density of waterlogged wood is completely accessed with the measured parameters. In the procedure, the calculations follow the normal formulae of volumetric mass determination. For facility and rapidity of calculations, it can be better to set up an automatic computation of the measured parameters. This can be done with the aid of a software data treatment like the EXCEL one.
The steps of described procedure and measured parameters were summarized in the table 1.

Table 1: Example of Excel foil for data computation in the procedure of determination of the conditional density of waterlogged woods samples (**R_{GC}**)

INPUT PARAMETERS		Abbreviation	Units
1	Free Beaker mass (on a 1/100th Sarthorius Mettler)	B_w	g
2	Volume of water (read volume)	V_{Wi}	mL
3	Total beaker + water mass	$TM_1 = B_w + W_M$	g
4	Sample dimensions in its three normal directions	R, T, A	mm
5	Sample mass (given by a 1/100th Sarthorius Mettler)	S_w	g
6	Total beaker + water + wood sample mass	$TM_2 = Bw + W_M + S_w$	g
7	Total volume of water + wood sample	V_{DW}	mL
8	Moisture content of small cut wood sample	$(M_i - M_f)/ M_i$	10^2. %
CALCULATIONS PROCEDURE			
9	Water mass (= TM_1 - Beaker mass)	$TM_1 - W_M$	g
10	Displaced water volume (= $V_{DW} - V_{Wi}$)	V_{ODW}	mL
11	Water volumetric mass (= water Mass /water Volume)	ρ_{water}	g/mL
12	Sample volume on basis of measured dimensions	R x T x A	$10^{-3}.cm^3$
13	Sample Apparent Volumetric mass	$\rho_{WSAPP} = S_W / V_{ODW}$	g/mL
14	Sample Apparent Density	$R_{GSAPP} = \rho_{WSAPP} / \rho_{water}$	-
15	Sample Maximum Water Content	$MWC=(M_i - M_f) /M_f$	10^2. %
OUTPUT DATUM			
16	Conditional density **R_{GC}** = [**R_{GSAPP} /(1+MWC/100)**]	**R_{GC}**	-

III- RESULTS AND DISCUSSIONS

In the case of EXCEL foil availability, values of the measured parameters might simply be logging at convenient places and obtained responses from computations are automatically put out. As the wood and specifically the waterlogged wood is a highly anisotropy material, the retained value for density of each of the studied wood species is the mean-value of at least six to eight trials. The correcting factor, that is the maximum water content value of wood specie, must also be a mean-value of several trials (at means six). However, in the real case of these archaeological artefacts, direct sampling on the woody objects and related tests are material destructive and so trials have been limited to only three.

The mean-values of all the required parameters might therefore be directly determined in the same set up calculation foil with their standard deviation as the case for conditional density.

Difference has been reasonably made between the wood density in absolutely dry state and the conditional density [Smith, 1954]. The latter is defined as the ratio of the mass of wood in absolutely dry state to its volume at maximum water saturation. It well characterises the real density of wood in its waterlogged state, as the determination of wood density in absolutely dry state is influenced by material shrinkage or retraction.

The new method for determination of conditional density has been applied to various waterlogged woods originated from different shipwrecks. The obtained results were those summarized in the columns 3 and 8 of table 2.

Comparison is also made using the Smith modified formula that only expressed conditional density (R_{GC}) as function of the maximum water content (MWC) through followed equation:

$$\frac{1}{R_{GC}} = \left[\left(\frac{MWC}{100} \right) + \frac{2}{3} \right] \frac{1}{R_{GC}} \qquad (1)$$

The author states that the maximum water content of wood is function of the specific gravity, on oven-dry weight green volume basis (S_{OG}), and the specific gravity of the wood substance (S_{WS}). He suggests that the specific gravity of a wood sample on oven-dry weight green volume could be estimated using its original relation expressed as:

$$S_{OG} = \frac{1}{\left[MWC + \left(\frac{1}{S_{WS}}\right)\right] S_{OG}} \quad (2)$$

Assumption of S_{WS} equals 1.5 drives to approximation of the fresh wood specific gravity S_{OG}. However, it's known that the waterlogged wood is highly different from the fresh wood because of the losses in some cell wall substances. The maximum water content of wood sample is expressed as the ratio of the initial mass minus the final mass per the final mass. It's the same as the commonly used moisture content, except that it is expressed in the dry basis.

The previous relation (1), which is a modified form of the equation (2), has in fact been recognised as usable for determination of the waterlogged wood conditional density.

In the proposed new method, the MWC of woods is also used in calculations. In reality, the measured parameters (Table 1) allow for determination of three kinds of density which are:

1- the wood density on the air, known as the ratio of sample mass to sample volume, as they are measured on the free air;

2- the wood density based on the estimated sample mass and sample volume in the water,

3- the density of desalted or deionised water, measured in real experimental conditions, through the recorded values for mass and volume of this water.

By weighing a wood sample in its waterlogged state (S_W), the obtained value contains both the two masses of the dry-matter (DM_W) and the inner water together (CM_W). This can therefore be expressed as $S_W = (DM_W + CM_W)$. When measuring the wood sample volume on the air (V_{WA}) and in the water (V_{ODW}), one acquires, not the sum of the volumes, but the common volume for the dry-matter and the contained water.

As high shrinkage occurs during the drying of waterlogged woods, the volume of dry sample is no longer the same as that of the wet. This leads to adoption of the conditional density for characterisation of waterlogged woods in place of any other form of density.

The volumetric mass of the moist wood (ρ_{WSAPP}) can be then written as following:

$$\rho_{WSAPP} = \frac{[DM_W + CM_W]}{V_{ODW}\,\rho_{WSAPP}} \quad (3)$$

and the conditional volumetric mass of wood (ρ_{WSCOND}) can be expressed as ratio of the mass of dry-matter to the measured sample volume in water:

$$\rho_{WSCOND} = \frac{DM_W}{V_{ODW}\,\rho_{WSCOND}} \quad (4)$$

As consequence, when comparing these two expressions, it can be clearly seen that the suppression of the moisture content of wood allows passing from the apparent density (ρ_{WSAPP}) relation (3) to the conditional density (ρ_{WSCOND}) definition (4).

Then, elimination of V_{ODW} term in those two expressions (3) and (4) gives followed equation:

$$\rho_{WSCOND} = \frac{\rho_{WSAPP}}{\left[\frac{1 + CM_W}{DM_W}\right]} \quad (5)$$

in which (CM_W / DM_W) is nothing other than the sample Maximum Water Content (MWC).

This equation (5) can afterwards be rewritten in the convenient form as follows:

$$\rho_{WSCOND} = \frac{\rho_{WSAPP}}{\left[\frac{1 + MWC}{100}\right]} \quad (6)$$

In the table 2, the obtained results from measurements of conditional density of forty two (42) waterlogged woods samples, by the proposed novel procedure (called **Method 2**) are shown in **columns 3** and **8**. Calculated values with the aid of the modified **Smith formula 1** (considered as classical **Method 1**) are also shown in **columns 5** and **10** for comparison. Nevertheless, two (02) remarks must be done on the table 2 content.

Table 2: Results of conditional density of waterlogged woods using the **New Method 2** (columns 3 and 8) and the calculated values by **Method 1** (columns 5 and 10)

Wood sample	MWC (%)	Method 2 (NEW)	σ	Method 1	Wood sample	MWC (%)	Method 2 (NEW)	σ	Method 1
S_1	354.81	**0.258**	0.088	**0.237**	S_{21}	757.14	**0.119**	0.014	**0.121**
S_2	452.23	**0.207**	0.062	**0.193**	S_{22}	704.26	**0.135**	0.010	**0.130**
S_3	321.54	**0.237**	0.061	**0.258**	S_{23}	357.86	**0.270**	0.068	**0.236**
S_4	343.19	**0.255**	0.053	**0.244**	S_{24}	457.26	**0.195**	0.021	**0.191**
$S_{5\ out}$	345.15	**0.260**	0.031	**0.243**	S_{25}	253.08	**0.329**	0.059	**0.313**
$S_{5\ in}$	281.73	**0.399**	0.021	**0.287**	S_{26}	315.40	**0.307**	0.125	**0.262**
S_6	552.99	**0.173**	0.033	**0.161**	S_{27}	552.94	**0.169**	0.025	**0.161**
S_7	301.63	**0.305**	0.096	**0.272**	S_{28}	759.64	**0.124**	0.044	**0.121**
S_8	292.85	**0.270**	0.052	**0.278**	S_{29}	854.42	**0.111**	0.007	**0.109**
S_9	230.08	**0.341**	0.049	**0.337**	S_{30}	1055.93	**0.090**	0.049	**0.089**
S_{10}	187.61	**0.407**	0.014	**0.393**	S_{31}	693.52	**0.149**	0.107	**0.132**
S_{11}	281.57	**0.273**	0.061	**0.287**	S_{32}	857.09	**0.114**	0.048	**0.108**
S_{12}	526.01	**0.175**	0.153	**0.169**	S_{33}	668.09	**0.144**	0.154	**0.136**
S_{13}	184.43	**0.383**	0.014	**0.398**	S_{34}	660.31	**0.149**	0.046	**0.138**
S_{14}	390.18	**0.224**	0.050	**0.219**	S_{35}	667.18	**0.148**	0.015	**0.136**
S_{15}	576.81	**0.153**	0.007	**0.155**	S_{36}	679.94	**0.146**	0.020	**0.134**
S_{16}	331.93	**0.260**	0.021	**0.251**	S_{37}	788.15	**0.119**	0.028	**0.117**
S_{17}	261.54	**0.314**	0.021	**0.305**	S_{38}	539.16	**0.160**	0.019	**0.165**
S_{18}	633.07	**0.141**	0.035	**0.143**	S_{39}	954.59	**0.098**	0.058	**0.098**
S_{19}	676.54	**0.140**	0.080	**0.135**	S_{40}	763.71	**0.127**	0.007	**0.120**
S_{20}	668.04	**0.150**	0.099	**0.136**	S_{41}	665.05	**0.139**	0.082	**0.137**

The first remark concerns exploitation of $\mathbf{R_{GC}}$ instead of ρ_{WSCOND} in this table 2. The wood density is calculated (see Table 1) as ratio of volumetric mass of samples to volumetric mass of water in measurements conditions. We simply choose to show these $\mathbf{R_{GC}}$ values with three decimals numbers because, when only two decimals are setting up, most of both the two results series become practically of equal values. This tendency can be better viewing in the figure 1 which depicts the normal probability plot for the two series of $\mathbf{R_{GC}}$ results. This figure reveals that it's difficult distinguishing those two series of recorded results as values are exceptionally superimposed to each other.

The second remark concerns this tacit use of unity value 1 for water density after application of Smith relation (1) in method 1, since this relation normally gives access to volumetric mass of wood in kg/m^3 unit. The volumetric mass of dry-substance of fresh wood was supposed to have a constant value of 1.5 kg/m^3.

Observation of these data in table 1 makes known that the obtained values, when applying the two determination methods for waterlogged wood density, are of the same order magnitudes. Except for a few wood samples on the studied forty-two, closest values are attained. These exceptions might be attributed to some slight introduced errors linked mainly with the reading of levels for displaced water volumes determination. Interfacial surface of gas-liquids separation in tubes is known not to be perfectly horizontal because of pressure difference that produces the meniscus. Surface concavity of liquid near the beaker wall might have a slight perturbation on exact value of the readied levels of the displaced water volumes in the procedure application.

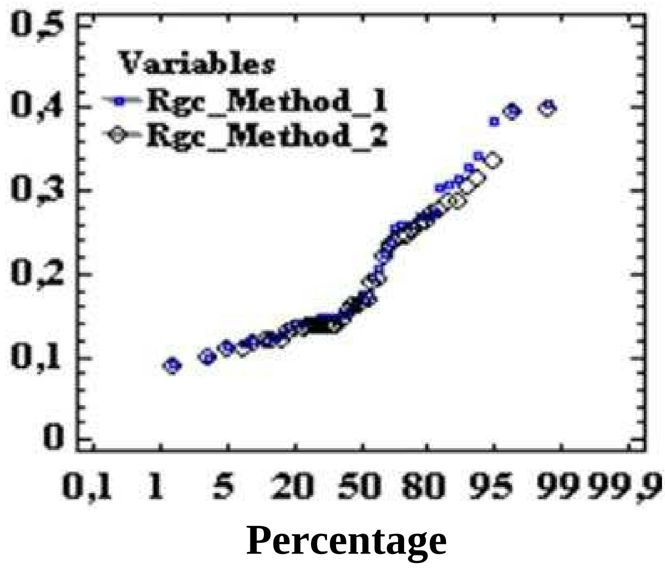

Figure 1: Normal probability plot for the two series of measured Rgc values.

Statistical analysis of data using StatGraphics software, a powerful means for such kind of study, allows showing the content of Figure 2. In the latter is depict the diagram of quantile - quantile plot for achieved results in applying the new method 2 (Equation 6) compared with those obtained using the relation (1). The Kolmogorov-Smirnov statistic test, that performed the computing of maximum distance between the cumulative distributions of the two types of values, shows that a good correlation exists between the two procedures. In intend of knowing which model adequately fitting these existing data and drawn correlation, Figure 3 is depicted on which is plot the fitted model with 99.00% prediction limits for these two compared methods. The output shows results of fitting a first order polynomial model to describe the relationship between values from R_{GC} Method 2 versus those from R_{GC} Method 1. The equation of the fitted model is labeled as:

$$R_{GC} \text{ Values [Method 2]} = 0.910 \times R_{GC} \text{ Values [Method 1]} + 0.009 \quad (7)$$

The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is $R^2 = 94.73$ %.

The proposed method is based on direct measurements and doesn't need any assumption on value of the wood dry-matter as it's done in the Smith modified relation (1). By this new procedure, all the errors that might be introduced with the classical assumption are avoided. Thus, more precise values are therefore accessed for the conditional density of wood. The obtained results also prove that this equation (1) can be considered as a very good approximation for evaluation of the waterlogged woods density. In this case, the new method arrives as a powerful means for insuring validity of the obtained density value when applying the R_{GC} formula (1). The proposed new approach is more precise, because the real state of wood substance is readily taken into account in ρ_{WSAPP} calculation. It's important to underline that the devised procedure avoids exploitation of this made assumption on basis of density value of 1.5 derived from the recorded data on the fresh wood dry-matter. As it's known, the waterlogged woods greatly differ from the fresh ones due to structural matter loss. However, it needs measurement of the specific mass in completion to simple determination of the moisture content that characterizes usage of the modified Smith formula (1).

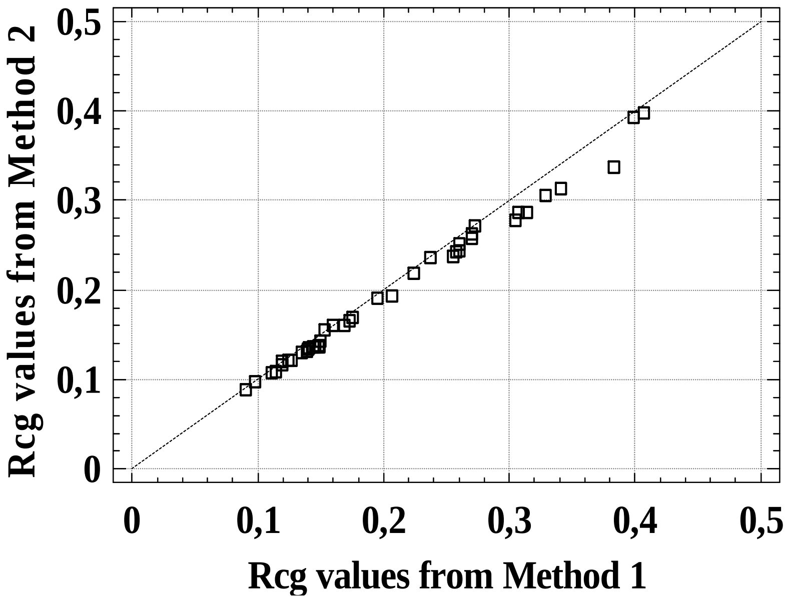

Figure 2: Quantile - quantile plot for results of the two R_{GC} methods applied to forty two (42) studied waterlogged woods samples

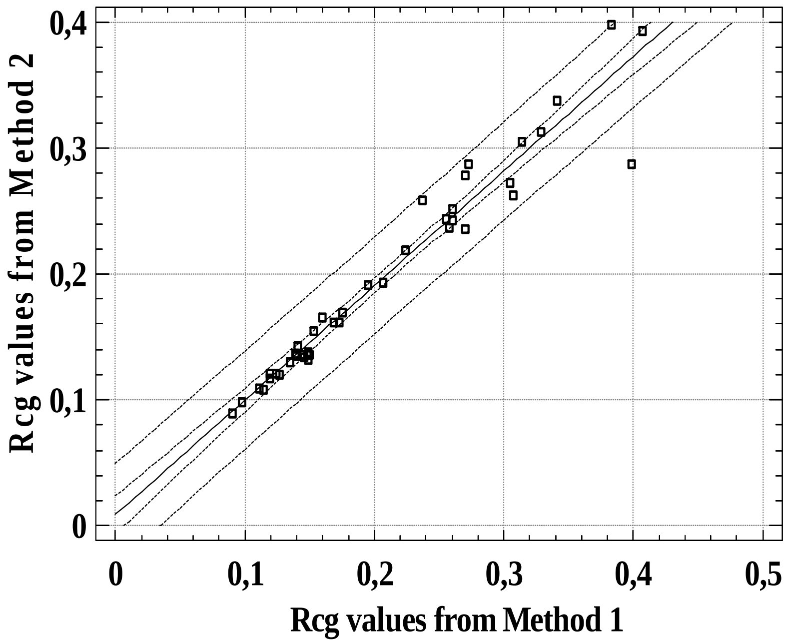

Figure 3: Plot of fitted model for results of the two R_{GC} methods applied to forty two (42) studied waterlogged woods samples.

Application of this new method doesn't take much more time than that needs for moisture content evaluation. All of the required data, for apparent density calculation, can then be determined during the course of water content measurements. Even so, it's preferable to make usage of the same wood samples which serve in apparent density measurements for the determination of the maximum water content of woods.

Although these achieved R_{GC} values from both two methods are practically of the same order, analysis of the plot curves of Figure 2 also makes known that, the application of method 2, as expressed through Equation 6, slightly underestimates the R_{GC} values from method 1 over about 0.25. The reason links with the fact that, in the devised new method 2, real values of dry-substance of waterlogged woods are taken into account conversely to the assumed constant 1.5-value of method 1. Accordingly, it outcomes that it's better proceeding in direct and practical measurement of R_{GC} density for waterlogged woods samples using the proposed new method 2 which avoids assumption of an adopted constant density of 1.5-value for dry-wood substance, as it's the case in method 1 procedure. It is also thought that such hypothesis might not still necessary hold with the decay woods. Since, waterlogged woods significantly differ from the fresh woods. Loss in constitutive materials of the wood cell walls often explains this difference. The suggested new procedure allows for overcoming such difficulty.

CONCLUSION

The developed novel method for evaluation of conditional density of waterlogged woods gives satisfactorily good results. For validation, the obtained results are compared with the recorded data from the classical R_{GC} relation derived from Smith. Very good correlation is obtained confirming validity of the proposed new method for measurement of the waterlogged woods conditional density. Application of modified Smith relation (1) can be considered as an approximate method for determination of conditional density of waterlogged woods. More precise measurements, based on a practical simple procedure, is then devised through the current method 2. Its use allows avoiding influence of such inserted errors that might be induced by assumption of constant density value for dry wood substance. It then comes as a powerful means for attainment of accurate R_{GC} measurement. It can also be well applied to some other moist products if these are totally water submersible. However, it can't hold with the fresh woods and materials that naturally contained gaseous pockets or cavities giving them ability for floating when water submersing.

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