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CALCULATION OF MOISTURE EXPANSION COEFFICIENT OF THE ABOVE KNEE PROSTHETIC SOCKET LAMINATION MATERIALS

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Abstract: The aim of this study is to calculate the moisture expansion coefficient of the above knee prosthetic socket lamination. Six laminations composite materials were used in manufacturing above knee prosthetic socket using a vacuum device. The reinforced materials of these laminations were Perlon, Fiberglass, and Nanocarbon powder, while the matrix material was Polyurethane resin. The experimental work included moisture absorption test to determine the time of absorption, and calculating percent moisture content and moisture expansion coefficient for these laminations. The humidity used in this study were (51, 75, 80, and 100 %).The results indicated that, lamination (2perlon+2fiberglass+2perlon) has the highest value of moisture expansion coefficient at (66.57×10^{-6}), while lamination (5perlon+2fiberglass+5perlon) has the lowest vaule of moisture expansion coefficient at (52.9×10^{-6}).

Keywords: *Above Knee Socket Lamination, Moisture Absorption Properties, Moisture Expansion Coefficient.*

حساب معامل التمدد الرطوبي لمواد وقب طرف سفلي صناعي اعلى الركبة

الخلاصة : الهدف من هذا البحث هو حساب معامل التمدد الرطوبي لصفائح وقب طرف سفلي اعلى الركبة. تم استخدام ستة انواع من المواد المركبة في تصنيع هذا الوقب. المواد التي استخدمت كمواد مقوية هي (Perlon, fiber glass, nanocarbon powder) بينما مادة الاساس هي (Polyurethane resin). الجانب العملي تضمن اختبار التشبع الرطوبي لمعرفة وقت التشبع، و حساب المحتوى الرطوبي و معامل التمدد الرطوبي. الرطوبة المستخدمة في هذا البحث هي (٥١، ٧٥، ٨٠، ١٠٠ %). النتائج اوضحت ان المادة المركبة المعززة ب(٢perlon+2fiberglass+2perlon) تمتلك اعلى معامل تمدد الرطوبي يصل الى (66.57×10^{-6}) بينما المادة المركبة المعززة ب (٥perlon+2fiberglass+5perlon) تمتلك اقل معامل تمدد الرطوبي يصل الى (52.9×10^{-6}).

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1. Introduction

Prosthesis or artificial limb is a device aims to substitute the loss of a limb. Above knee prosthetic consists of several components including (socket, knee, shank, ankle and foot). The socket can be considered as the most important part of above knee prosthesis, which interfaces between the amputee's stump and prosthesis [1]. The materials used in manufacturing socket lamination must be plastic, nontoxic, and strength-to-weight ratio is reasonable [2]. Some materials used in manufacturing the sockets include: fiber glass, kevlar fibers, carbon fibers, and thermoplastic polymers [3]. These materials can be exposed to moisture during their service life. When exposed to moisture, these materials will absorb moisture. In general, when a material is exposed to moisture, it will swell (expand) [4]. The change in dimensions due to this expansion are measured by the coefficient of moisture expansion defined as the change in the linear dimension per unit length per unit change in weight of moisture content per unit weight [5]. Moisture expansion coefficient of composite materials was calculated by investigators. Pavankiran, et al. [6] calculated moisture expansion coefficient of unidirectional laminate made of carbon fiber reinforced epoxy. They found that, the moisture expansion coefficient is ($1.92 \times 10^{-3}/$ %) for this laminate. Ernest [7] determined moisture expansion coefficient of unidirectional laminate manufactured from graphite reinforced with epoxy. He showed that, the moisture expansion coefficient for this laminate is equal to (29.2×10^{-6}). This study focused on calculation of the moisture expansion coefficient of the above knee prosthetic socket lamination materials.

2. Experimental Work

2.1 Materials

In this work, the reinforced materials used in manufacturing of the above knee socket laminations were (Perlon stockinet white, Fiberglass stockinet, Carbon Nanopowder Particles 80nm), while the matrix material was lamination resin 80:20 polyurethane. The procedures of manufacturing above knee socket laminations includes:-

1. The gypsum mold as shown in fig. (1a) was fixed on a stand and connected it with the vacuum device as shown in fig. (1) through tubes. Then, the inner (PVA) bag was fitted on gypsum mold to prevent adhesion of the gypsum mold with the resin.
2. The perlon stockinet and fiberglass stockinet were stacked according to the laminating lay-up given in Table (1). Then, the outer (PVA) was fitted over the laminations.
3. The lamination resin 80:20 polyurethane was mixed with hardener for laminations without carbon nanopowder. Then, the matrix was poured inside the outside (PVA) bag. For lamination with carbon nanopowder, the lamination resin 80:20 polyurethane was mixed with (1 wt%) carbon nanopwoder using Ultrasonic mixing as shown in fig. (1c) for 30 minutes. Then mixed with hardener. Finally, the matrix was poured inside the outside (PVA) bag.

4. Using the vacuum device which operates at a pressure of (-0.8 bar) for 20 minutes until the lamination becomes cold and then lifted from the gypsum mold. Finally, laminations were cut according to need.

a) Gypsum mold b) Vacuum device c) Ultrasonic mixing device

Fig. (1) Equipment and tools used in manufacturing A-K socket lamination

Table (1) The laminations manufacturing with different lay-up

Laminations	*Lay-up symbol*	*Total No. of layers*	*Laminations lay-up*
Lamination 1	525	12	(5perlon+2fiber glass+5perlon)
Lamination 2	424	10	(4perlon+2fiber glass+4perlon)
Lamination 3	323	8	(3perlon+2fiber glass+3perlon)
Lamination 4	222	6	(2perlon+2fiber glass+2perlon)
Lamination 5	505	10	(5perlon+0fiber glass+5perlon)
Lamination 6	505+CNP	12	(5perlon+2fiber glass+5perlon) +(1 wt% CNP)

2.2 Moisture Absorption Properties

The moisture absorption properties for all laminations were found according to ASTM D 5229 [8]. The humidity that was used in this study were taken for the Iraqi climate for the year 2013 as obtained from the Iraqi Meteorological Organization and Seismology. This study focused on humidity for February, April, June, and August at (100, 75, 51, and 80 %), respectively. The equipments used in moisture absorption test were digital vernier, digital sensitive weighing, and hygrothermal device as shown in fig. (2).

Digital vernier Digital sensitive weighing Hygrothermal device

Fig. (2) The equipment used in moisture absorption test

The procedures for calculating the moisture absorption properties include:

1- A square plate was prepared for each lamination sample with dimensions that satisfy the relation [8]:

$$\frac{\mathbf{L}}{\mathbf{t}} \geq \mathbf{100} \tag{1}$$

In this work, the ratio between the length to thickness is chosen 100. Then, the Weight of the square plate was measured by digital sensitive weighing. Table (2) shows the dimensions and weight of the square plates for each lamination.

Table (2). The dimensions and weight of the square plate for all laminations

Lay-up symbol	*Length (mm)*	*Thickness (mm)*	*Mass (g)*
222	325	3.25	417.7
323	380	3.8	638.4
424	410	4.1	862.9
525	470	4.7	1174
505	310	3.1	728.3
505+CNP	310	3.1	728.3

2- Hygrothermal device was operated at humidity of (51, 75, 80, and 100 %) and temperature (25℃). Then, the plate was put inside the hygrotheraml device.

3- Then the percent moisture content at each time interval was calculated using Eq.(2) until is reaching the value estimated by Eq. (3) [8].

$$\boldsymbol{M}\,\% = \frac{\boldsymbol{w_f} - \boldsymbol{w_i}}{\boldsymbol{w_i}} \times \mathbf{100} \tag{2}$$

$$|\boldsymbol{M_i} - \boldsymbol{M_{i-1}}| < \mathbf{0.01}\,\% \tag{3}$$

2.3 Moisture Expansion Coefficient

The square plate of each lamination was exposed to moisture absorpted and the percent of moisture content for all the values of humidity that were used in this study was calculated. In addition, the change of length due to hygroscopic effect was measured by a digital vernier. The moisture strain was determined according to Eq.(4) [5].

$$\varepsilon_H = \frac{\Delta l}{l_o} \tag{4}$$

The relationship between the moisture strain and the percent moisture content was plotted. The moisture expansion coefficient was determined according to Eq.(5) [5].

$$\beta = \frac{\varepsilon_H}{M\,(\%)} \tag{5}$$

3. Results and Discussion

3.1 Moisture Absorption results

The moisture absorption properties are listed in table (3) and indicated in figure (3). This figure shows the moisture absorption with the root of time according to ASTM 5229 for each lamination. It can be seen from fig.(3) that with increasing the time, moisture absorption is increased. The moisture absorption for laminations (222, 505, and, 505+CNP) is become steady after (64 hours) for each moisture used in this study. But, the moisture absorption for laminations (323, 424, and 525) is become steady after (64 hours) when the humidity is (51%), and stabilized after (81 hours) when the humidity is (75, 80, and 100 %).

Table (3) Moisture Absorption Properties for each lamination

Lamination	*HR %*	W_i *(g)*	W_f *(g)*	*M (%)*	L_i *(mm)*	L_f *(mm)*	*t (hour)*
222	51	417.7	419.92	0.5315	325	325.01	64
	75		425	1.762		325.03	
	80		425.67	1.908		325.04	
	100		428.91	2.683		325.06	
323	51	638.4	641.31	0.452	380	380.01	64
	75		647.78	1.466		380.03	81
	80		648.59	1.593		380.04	81
	100		653.38	2.343		380.05	81
424	51	862.9	866.54	0.421	410	410.01	64
	75		875.32	1.439		410.03	81
	80		876.62	1.59		410.04	81
	100		882.43	2.26		410.06	81
525	51	1174	1178.33	0.36	470	470.01	64
	75		1188.89	1.268		470.03	81
	80		1190.72	1.423		470.04	81
	100		1198.02	2.04		470.05	81
505	51	378.8	380.89	0.55	310	310.01	64
	75		385.71	1.823		310.03	
	80		386.22	1.958		310.04	
	100		389.22	2.75		310.05	
505+CNP	51	378.8	380.81	0.53	310	310.01	64
	75		385.17	1.68		310.03	
	80		385.77	1.83		310.04	
	100		388.86	2.65		310.05	

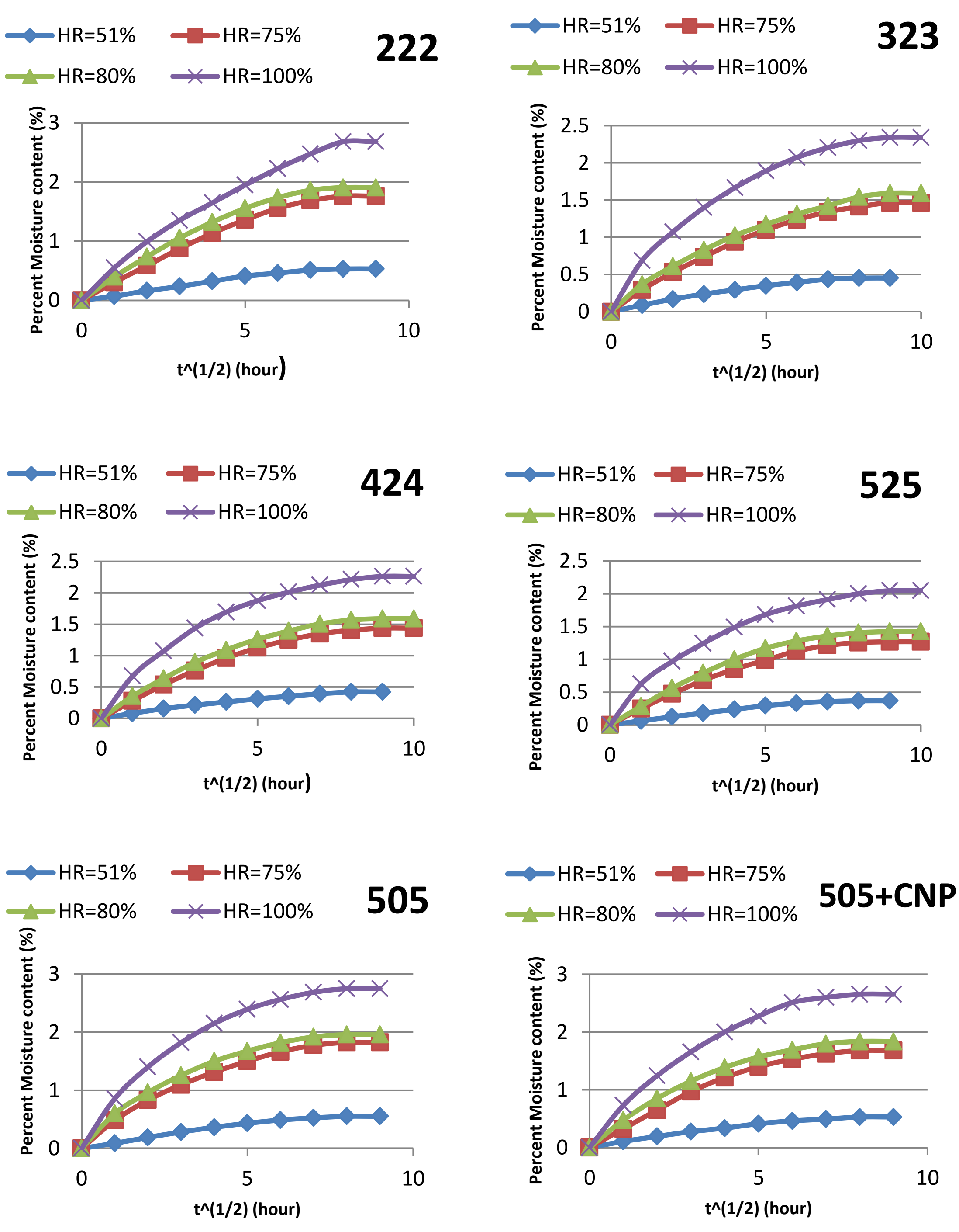

Fig. (3) Moisture absorption for each lamination

Also, it is clear from table (3) that, lamination (525) gained most weight up to (24.02 g) at moisture 100 %, and lamination (505+CNP) gained least weight up to (2.01 g) at moisture 51%. Finally, it can be seen from table (3) that the greatest value of the percent moisture content is found in (505) up to (2.75 %) at moisture 100%, and the smallest value of the percent moisture content is found in (525) up to (0.36 %) at moisture 51%.

3.2 Moisture Expansion Coefficient results

The moisture strain with the percent moisture content for all laminations are shown in fig. (4). The moisture expansion coefficient for each lamination was found from slope for this figure. The moisture expansion coefficient for all laminations is shown in fig. (5). It is clear from figure (5) that, lamination (222) has the higher value of the moisture expansion coefficient up to (66.57×10^{-6}) because the percent moisture content is higher, and the lower value of the moisture expansion coefficient is found in lamination (525) up to (52.9×10^{-6}) because the percent moisture content is lower.

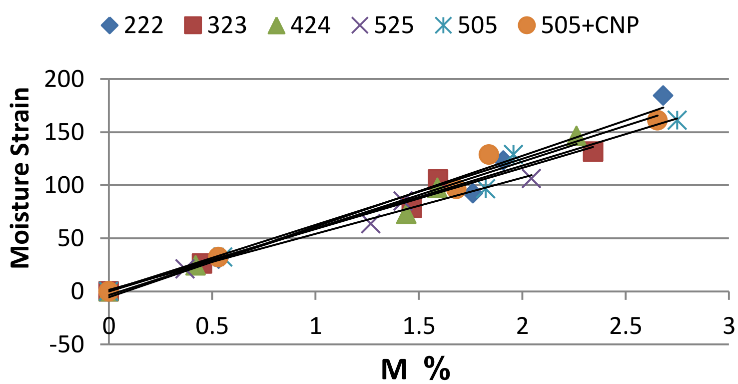

Fig. (4) (ε_H - M%) for each lamination

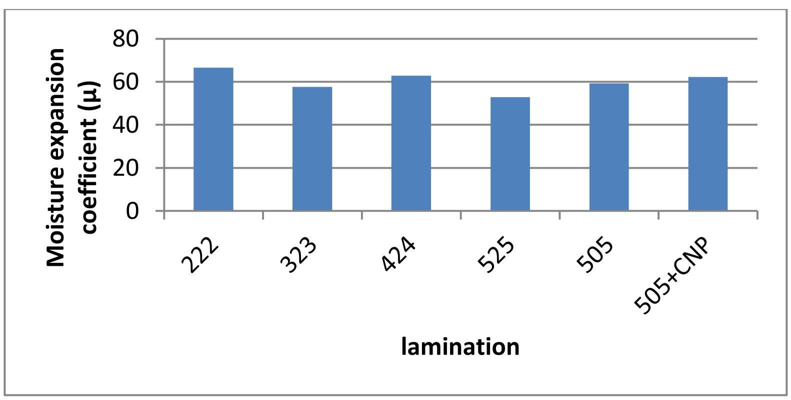

Fig. (5) Moisture Expansion Coefficient (β) for each lamination

4. Conclusions

1. The moisture absorption for each lamination increased with time until saturation. The time of moisture absorption for each lamination at (51%) is (64 hour). But, the time of moisture absorption for laminations (222, 505, 505+CNP) at (75, 80, and 100 %) is (64 hour),and the time of moisture absorption for laminations (323, 424, 525) at (75, 80, and 100 %) is (81 hour).

2. Lamination (222) has higher moisture expansion coefficient up to (66.57×10^{-6}), while lamination (525) has lower moisture expansion coefficient up to (52.9×10^{-6}).

Abbreviations

t: time after moisture absorption (hour)
L_i: length before moisture absorption (mm)
L_f: length after moisture absorption (mm)
Δl: change of length due to hygroscopic effect (mm)
W_i: Weight before moisture absorption (g)
W_f: Weight after moisture absorption (g)
ε_H: Moisture Strain (m/m)
M: Percent Moisture Content (%)
HR: Humidity (%)
β: Moisture Expansion Coefficient ((kg/kg)/(m/m))

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