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The Application of Rule of Mixtures to Fiber-Reinforced Composites(3)[1]

— Determination of Constant "a" and "b" for the Modified Rule of Mixtures Applied to Fiber-Reinforced, Sulfur-Based Composites —

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목재 섬유 複合材에 混合理論의 적용에 관한 研究(3)[1]

—硫黃 化合物을 사용한 木材 纖維 複合材에 수정된 混合理論의 常數 決定—

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要 約

섬유의 방향성이 무질서한 composites에 적용되는 Smith와 Cox의 理論을 포함한 Paul과 Jones의 混合理論式은 硫黃 化合物을 사용하여 제조한 목재섬유 複合材에도 一次的인 linear regression constant가 주어질 때는 사용할 수가 있음을 보여준다.

$E_c = \frac{1}{3} aE_f V_f + bE_m V_m$으로 표시된 이 linear regression form에 math. rom pack을 사용한 Hewlett Packard 75C(HP 75C) computer의 계산 결과는 목재 섬유 複合材에 사용된 matrix의 종류, 섬유판의 밀도와 목재 및 목질 섬유의 종류에 관계없이 a = 3.27~3.54와 b = −2.47~−2.80의 일정한 범위의 값을 보여주므로, 지금까지 無질서한 방향성을 지닌 長섬유로 된 複合材에만 적용되어 왔던 Paul과 Jones의 混合理論과 이것과 같은 방향을 지닌 短 섬유로 된 木材나 木質 섬유 composites에도 적용될 수 있음을 증명하고 있다.

Summary

It is shown that Paul and Jones' Rule of Mixtures modified by Smith and Cox's theory can be used for the fiber-reinforced, sulfur-based composites, when the constant for the linear regression equation is given.

The computation results, programmed by Hewlett Packard 75C (HP 75C) using math rom pack for the linear regression form, expressed as $Ec = \frac{1}{3} aE_f V_f + bE_m V_m$, turn out to be a =3.27−3.54 b=-2.47~−2.80.

This results indicate that the factors such as density of fiber mat and the amount of matrix used have nothing for affecting the numerical value of the constants a and b of the linear regression form.

Conclusively this results also show that the Paul and Jones' Rule of Mixtures which has been used for the composites made by randomly-oriented long fiber can also be used for the composites made by short fiber with the same fiber orientation such as wood and lignocellulosic fibers.

Key words: fiber-reinforced composites, Smith and Cox's theory, Paul and Jones' rule, fiber orientation.

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metal stops at the edges of the mats.

Pressed fiber mats were cut into 2-inch by 5½-inch specimens. These were immersed in molten sulfur modified by tall oil and polyester, which characterizes synthetic resinous material at 135°-140°C, until they were thoroughly saturated. The time required for thorough saturation varied from 10 to 30 minutes.

Instron Tester was used for mechanical strength properties of the composites, which are modulus of elasticity and modulus of rupture.

In order to apply the experimental results to Bryant and Lee's hypothesis, primarily linear regression form is examined using Hewlett Packard 75C (HP 75C) computer with mathematic rom pack.

1. Introduction

Bryant and Lee identified in their early papers (1983)[1,2] that the modified rule of mixtures applicable to the composites having random fiber orientation and long fiber in it can be prepared on the basic equation of Paul and Jones' Rule of Mixtures using Smith and Cox's theory.

Bryant and Lee also applied this new modified rule of mixtures to the experimental results of fiber-reinforced, sulfur-based composites (1983).[1,2] They found that the new modified rule of mixtures can only be applicable in a certain condition of fiber mat and matrix used in the composites, and also it is very difficult to use this modified rule of mixtures as the generalized equation for the composites (1981).[3,4] In this context, Bryant and Lee proposed their hypothesis as the first attempt in the papers (1983)[1,2] that the modified rule of mixture will have a constant of the first degree on the equation of the modified rule of mixtures expressed as $Ec = \frac{1}{3} a E_f V_f + b E_m V_m$. It is assumed that the constants of the first degree of the equation can be obtained by applying the experimental results to the equation, using linear regression form programmed.

2. Experimental procedure

A series of fiber mats were prepared from kraft pulpmill screening rejects provided by the Crown Zellerback pulpmill at Wallula, Oregon in U.S.A.. Rice straw pulp was made by soaking chopped straw in a 1% NaOH solution overnight and beating it for about 2 minutes in a laboratory model Hollander. After beating, the pulp was thoroughly washed to remove pith and fines.

Fiber mats were made in a 12-inch-square sheet mold, using enough fiber to produce pressed mats of about 1/8-inch thickness at the required density. In order to control density, mats were first air dried and then pressed between screens in a steam-heated laboratory hot press using 1/8-inch-thick metal stops at the edges of the mats.

3. Results and discussion

In order to calculate the constants a and b in the Bryant and Lee's hypothesis, the experimental data used are followed in the Tables.

Table 1. Mechanical strength properties and volume fraction of constituents of the composites.
Fiber source : rice straw
Matrix : the compound(sulfur + tall oil)
Mechanical Strength unit: psi.

E_c	E_f	E_m	V_m	V_f
31.4x10⁴	233x10⁴	26x10⁴	0.7853	0.1001
32.1x10⁴	"	"	0.7841	0.1012
33.3x10⁴	"	"	0.7830	0.1023
34.6x10⁴	"	"	0.7820	0.1032
35.1x10⁴	"	"	0.7809	0.1041
36.7x10⁴	"	"	0.7794	0.1055
37.7x10⁴	"	"	0.7783	0.1062
39.0x10⁴	"	"	0.7774	0.1074
41.1x10⁴	"	"	0.7764	0.1081
41.8x10⁴	"	"	0.7753	0.1092
42.1x10⁴	"	"	0.7742	0.1103
43.0x10⁴	"	"	0.7732	0.1114
44.0x10⁴	"	"	0.7721	0.1124
45.1x10⁴	"	"	0.7710	0.1133
45.9x10⁴	"	"	0.7701	0.1145
47.3x10⁴	"	"	0.7690	0.1157
48.3x10⁴	"	"	0.7671	0.1166
49.6x10⁴	"	"	0.7660	0.1186
50.5x10⁴	"	"	0.7651	0.1197
51.1x10⁴	"	"	0.7643	0.1209

E_c	E_f	E_m	V_m	V_f
52.2x10^4	233x10^4	26x10^4	0.7632	0.1219
53.4x10^4	〃	〃	0.7621	0.1230
54.1x10^4	〃	〃	0.7610	0.1242
55.3x10^4	〃	〃	0.7600	0.1254
56.2x10^4	〃	〃	0.7591	0.1268
57.1x10^4	〃	〃	0.7582	0.1277
57.8x10^4	〃	〃	0.7573	0.1289
58.1x10^4	〃	〃	0.7560	0.1300
58.8x10^4	〃	〃	0.7550	0.1310
59.1x10^4	〃	〃	0.7541	0.1321
61.1x10^4	〃	〃	0.7530	0.1331
62.8x10^4	〃	〃	0.7522	0.1339
63.4x10^4	〃	〃	0.7510	0.1348
65.1x10^4	〃	〃	0.7500	0.1355
66.6x10^4	〃	〃	0.7491	0.1367
67.8x10^4	〃	〃	0.7480	0.1379
68.3x10^4	〃	〃	0.7470	0.1390
69.6x10^4	〃	〃	0.7462	0.1403
70.7x10^4	〃	〃	0.7450	0.1412
72.2x10^4	〃	〃	0.7440	0.1424
73.3x10^4	〃	〃	0.7430	0.1435
74.1x10^4	〃	〃	0.7421	0.1447
75.2x10^4	〃	〃	0.7383	0.1495
77.3x10^4	〃	〃	0.7370	0.1510
78.1x10^4	〃	〃	0.7361	0.1524
79.2x10^4	〃	〃	0.7320	0.1581
80.1x10^4	〃	〃	0.7310	0.1602
81.1x10^4	〃	〃	0.7300	0.1621
82.6x10^4	〃	〃	0.7290	0.1643
83.4x10^4	〃	〃	0.7282	0.1659
84.0x10^4	〃	〃	0.7271	0.1681

Table 2. Mechanical strength properties and volume fraction of constituents of the composites.
Fiber Source : pulp rejects
Matrix : the compound (sulfur + tall oil)

E_c	E_f	E_m	V_m	V_f
68.1x10^4	233x10^4	26x10^4	0.7533	0.1330
69.4x10^4	〃	〃	0.7544	0.1344
70.0x10^4	〃	〃	0.7527	0.1364
71.1x10^4	〃	〃	0.7510	0.1384
72.2x10^4	〃	〃	0.7510	0.1403
73.3x10^4	〃	〃	0.7500	0.1428
73.9x10^4	〃	〃	0.7481	0.1457
75.2x10^4	〃	〃	0.7465	0.1473
76.3x10^4	〃	〃	0.7439	0.1498
77.1x10^4	〃	〃	0.7428	0.1509
78.0x10^4	〃	〃	0.7418	0.1520
79.1x10^4	〃	〃	0.7407	0.1530
80.2x10^4	〃	〃	0.7400	0.1540
81.1x10^4	〃	〃	0.7393	0.1552
82.1x10^4	〃	〃	0.7381	0.1561
83.4x10^4	〃	〃	0.7370	0.1574

E_c	E_f	E_m	V_m	V_f
84.2x10^4	233x10^4	26x10^4	0.7355	0.1582
85.0x10^4	〃	〃	0.7356	0.1594
86.1x10^4	〃	〃	0.7350	0.1604
87.3x10^4	〃	〃	0.7345	0.1613
88.8x10^4	〃	〃	0.7340	0.1628
89.1x10^4	〃	〃	0.7330	0.1642
90.3x10^4	〃	〃	0.7322	0.1657
93.1x10^4	〃	〃	0.7315	0.1670
93.4x10^4	〃	〃	0.7303	0.1685
94.1x10^4	〃	〃	0.7289	0.1699
95.4x10^4	〃	〃	0.7277	0.1713
96.7x10^4	〃	〃	0.7264	0.1725
97.7x10^4	〃	〃	0.7253	0.1740
98.4x10^4	〃	〃	0.7244	0.1756
99.6x10^4	〃	〃	0.7230	0.1773
101.0x10^4	〃	〃	0.7221	0.1783
102.4x10^4	〃	〃	0.7210	0.1800
103.7x10^4	〃	〃	0.7201	0.1814
104.4x10^4	〃	〃	0.7198	0.1826
105.6x10^4	〃	〃	0.7189	0.1838
106.1x10^4	〃	〃	0.7181	0.1850
108.0x10^4	〃	〃	0.7174	0.1862
109.2x10^4	〃	〃	0.7166	0.1870
110.1x10^4	〃	〃	0.7154	0.1880
112.0x10^4	〃	〃	0.7147	0.1890
113.1x10^4	〃	〃	0.7136	0.1907
114.4x10^4	〃	〃	0.7127	0.1916
115.2x10^4	〃	〃	0.7120	0.1925
116.1x10^4	〃	〃	0.7117	0.1937
117.0x10^4	〃	〃	0.7111	0.1951
118.1x10^4	〃	〃	0.7104	0.1958
119.2x10^4	〃	〃	0.7097	0.1972
120.0x10^4	〃	〃	0.7084	0.1984
121.1x10^4	〃	〃	0.7073	0.1992
122.0x10^4	〃	〃	0.7066	0.2001
123.1x10^4	〃	〃	0.7059	0.2011
124.4x10^4	〃	〃	0.7051	0.2025
126.1x10^4	〃	〃	0.7042	0.2038
126.6x10^4	〃	〃	0.7031	0.2047
128.1x10^4	〃	〃	0.7024	0.2062
129.3x10^4	〃	〃	0.7016	0.2070
131.0x10^4	〃	〃	0.7011	0.2075
132.0x10^4	〃	〃	0.7001	0.2081
133.1x10^4	〃	〃	0.6987	0.2104
134.2x10^4	〃	〃	0.6970	0.2126
135.1x10^4	〃	〃	0.6964	0.2135
136.3x10^4	〃	〃	0.6946	0.2150
137.0x10^4	〃	〃	0.6940	0.2161
138.1x10^4	〃	〃	0.6932	0.2174
139.0x10^4	〃	〃	0.6911	0.2182
141.1x10^4	〃	〃	0.6906	0.2191
142.6x10^4	〃	〃	0.6901	0.2204
143.3x10^4	〃	〃	0.6894	0.2211
144.6x10^4	〃	〃	0.6889	0.2227

E_c	E_f	E_m	V_m	V_f
145.4x10^{4}	233x10^{4}	26x10^{4}	0.6884	0.2232
146.0x10^{4}	〃	〃	0.6880	0.2245
147.1x10^{4}	〃	〃	0.6889	0.2258
149.4x10^{4}	〃	〃	0.6867	0.2266
149.9x10^{4}	〃	〃	0.6849	0.2279
151.6x10^{4}	〃	〃	0.6841	0.2289

Table 3. Mechanical strength properties and volume fraction of constituents of the composites
Fiber source : rice straw
Matrix : the synthetic resin (sulfur + polyester)

E_c	E_f	E_m	V_m	V_f
28.1x10^{4}	233x10^{4}	18x10^{4}	0.7867	0.0993
29.1x10^{4}	〃	〃	0.7859	0.0998
29.8x10^{4}	〃	〃	0.7850	0.1004
31.2x10^{4}	〃	〃	0.7849	0.1014
32.5x10^{4}	〃	〃	0.7831	0.1022
33.3x10^{4}	〃	〃	0.7822	0.1034
34.2x10^{4}	〃	〃	0.7810	0.1042
35.3x10^{4}	〃	〃	0.7795	0.1055
35.9x10^{4}	〃	〃	0.7782	0.1063
37.0x10^{4}	〃	〃	0.7773	0.1075
38.2x10^{4}	〃	〃	0.7764	0.1083
39.1x10^{4}	〃	〃	0.7752	0.1092
40.0x10^{4}	〃	〃	0.7743	0.1103
41.4x10^{4}	〃	〃	0.7730	0.1110
42.6x10^{4}	〃	〃	0.7724	0.1123
43.3x10^{4}	〃	〃	0.7721	0.1140
44.7x10^{4}	〃	〃	0.7710	0.1141
44.9x10^{4}	〃	〃	0.7704	0.1149
46.2x10^{4}	〃	〃	0.7692	0.1157
47.3x10^{4}	〃	〃	0.7671	0.1178
48.1x10^{4}	〃	〃	0.7660	0.1184
49.2x10^{4}	〃	〃	0.7651	0.1197
50.1x10^{4}	〃	〃	0.7645	0.1209
51.4x10^{4}	〃	〃	0.7633	0.1218
52.2x10^{4}	〃	〃	0.7626	0.1230
53.3x10^{4}	〃	〃	0.7610	0.1242
54.0x10^{4}	〃	〃	0.7601	0.1255
55.6x10^{4}	〃	〃	0.7588	0.1266
57.1x10^{4}	〃	〃	0.7577	0.1290
57.9x10^{4}	〃	〃	0.7562	0.1301
58.4x10^{4}	〃	〃	0.7554	0.1312
60.6x10^{4}	〃	〃	0.7546	0.1322
61.2x10^{4}	〃	〃	0.7534	0.1334
62.3x10^{4}	〃	〃	0.7526	0.1338
63.4x10^{4}	〃	〃	0.7510	0.1344
64.2x10^{4}	〃	〃	0.7502	0.1357
66.1x10^{4}	〃	〃	0.7494	0.1368
68.2x10^{4}	〃	〃	0.7481	0.1378
70.1x10^{4}	〃	〃	0.7470	0.1387
71.1x10^{4}	〃	〃	0.7462	0.1407
71.8x10^{4}	233x10^{4}	18x10^{4}	0.7451	0.1416
72.6x10^{4}	〃	〃	0.7440	0.1424
73.1x10^{4}	〃	〃	0.7426	0.1437
75.2x10^{4}	〃	〃	0.7422	0.1449
75.8x10^{4}	〃	〃	0.7392	0.1491
76.1x10^{4}	〃	〃	0.7372	0.1512
78.3x10^{4}	〃	〃	0.7362	0.1527
78.8x10^{4}	〃	〃	0.7321	0.1584
79.1x10^{4}	〃	〃	0.7316	0.1606
79.7x10^{4}	〃	〃	0.7304	0.1627
81.1x10^{4}	〃	〃	0.7291	0.1647
81.4x10^{4}	〃	〃	0.7284	0.1657
81.9x10^{4}	〃	〃	0.7277	0.1680

Table 4. Mechanical strength properties and volume fraction of constituents of the composites
Fiber Source : pulp rejects
Matrix : synthetic resin (sulfur + polyester)

E_c	E_f	E_m	V_m	V_f
65.0x10^{4}	233x10^{4}	18x10^{4}	0.7553	0.1330
66.6x10^{4}	〃	〃	0.7544	0.1344
67.8x10^{4}	〃	〃	0.7527	0.1364
68.2x10^{4}	〃	〃	9.7513	0.1385
69.6x10^{4}	〃	〃	0.7510	0.1403
70.2x10^{4}	〃	〃	0.7500	0.1428
71.1x10^{4}	〃	〃	0.7481	0.1460
72.0x10^{4}	〃	〃	0.7467	0.1475
73.1x10^{4}	〃	〃	0.7449	0.1487
75.2x10^{4}	〃	〃	0.7439	0.1498
76.4x10^{4}	〃	〃	0.7428	0.1509
76.7x10^{4}	〃	〃	0.7418	0.1520
77.1x10^{4}	〃	〃	0.7407	0.1530
77.8x10^{4}	〃	〃	0.7400	0.1541
78.1x10^{4}	〃	〃	0.7391	0.1552
78.9x10^{4}	〃	〃	0.7380	0.1560
80.1x10^{4}	〃	〃	0.7370	0.1573
81.1x10^{4}	〃	〃	0.7359	0.1581
82.3x10^{4}	〃	〃	0.7356	0.1594
83.3x10^{4}	〃	〃	0.7350	0.1604
84.6x10^{4}	〃	〃	0.7345	0.1613
85.7x10^{4}	〃	〃	0.7340	0.1628
86.2x10^{4}	〃	〃	0.7330	0.1642
87.1x10^{4}	〃	〃	0.7322	0.1657
88.2x10^{4}	〃	〃	0.7315	0.1670
89.1x10^{4}	〃	〃	0.7303	0.1685
90.6x10^{4}	〃	〃	0.7289	0.1699
91.4x10^{4}	〃	〃	0.7277	0.1713
92.6x10^{4}	〃	〃	0.7266	0.1729
93.1x10^{4}	〃	〃	0.7254	0.1741
94.2x10^{4}	〃	〃	0.7244	0.1756
94.6x10^{4}	〃	〃	0.7230	0.1773
95.5x10^{4}	〃	〃	0.7220	0.1784

E_c	E_f	E_m	V_m	V_f
96.7x10^4	233x10^4	18x10^4	0.7209	0.1801
97.4x10^4	〃	〃	0.7220	0.1784
98.1x10^4	〃	〃	0.7209	0.1801
99.6x10^4	〃	〃	0.7201	0.1814
100.6x10^4	〃	〃	0.7198	0.1826
101.2x10^4	〃	〃	0.7189	0.1839
103.1x10^4	〃	〃	0.7180	0.1850
103.7x10^4	〃	〃	0.7172	0.1861
104.4x10^4	〃	〃	0.7163	0.1871
105.2x10^4	〃	〃	0.7154	0.1880
106.6x10^4	〃	〃	0.7143	0.1892
107.1x10^4	〃	〃	0.7134	0.1903
180.4x10^4	〃	〃	0.7125	0.1913
109.6x10^4	〃	〃	0.7120	0.1925
110.1x10^4	〃	〃	0.7117	0.1938
111.2x10^4	〃	〃	0.7110	0.1949
114.2x10^4	〃	〃	0.7101	0.1959
114.6x10^4	〃	〃	0.7091	0.1970
115.0x10^4	〃	〃	0.7082	0.1981
116.1x10^4	〃	〃	0.7073	0.1992
117.2x10^4	〃	〃	0.7064	0.2003
118.6x10^4	〃	〃	0.7055	0.2015
119.6x10^4	〃	〃	0.7050	0.2027
121.1x10^4	〃	〃	0.7042	0.2038
121.4x10^4	〃	〃	0.7033	0.2050
122.6x10^4	〃	〃	0.7024	0.2061
123.4x10^4	〃	〃	0.7016	0.2070
123.8x10^4	〃	〃	0.7010	0.2075
125.0x10^4	〃	〃	0.7001	0.2091
126.0x10^4	〃	〃	0.6993	0.2102
126.8x10^4	〃	〃	0.6977	0.2114
128.1x10^4	〃	〃	0.6970	0.2124
129.0x10^4	〃	〃	0.6962	0.2135
129.9x10^4	〃	〃	0.6954	0.2146
131.0x10^4	〃	〃	0.6940	0.2161
131.9x10^4	〃	〃	0.6932	0.2172
133.3x10^4	〃	〃	0.6924	0.2183
134.1x10^4	〃	〃	0.6916	0.2194
135.6x10^4	〃	〃	0.6908	0.2202
136.4x10^4	〃	〃	0.6901	0.2214
137.5x10^4	〃	〃	0.6893	0.2225
138.1x10^4	〃	〃	0.6887	0.2236
139.1x10^4	〃	〃	0.6880	0.2247
141.0x10^4	〃	〃	0.6868	0.2258
142.2x10^4	〃	〃	0.6861	0.2269
143.6x10^4	〃	〃	0.6853	0.2279
144.4x10^4	〃	〃	0.6847	0.2286
145.2x10^4	〃	〃	0.6840	0.2294

When $Ec = \frac{1}{3} aE_fV_f + bE_mV_m$ is admitted to calculate the "Bryant and Lee's constant", a and b, it is natural to adopt linear regression form using Hewlett Packard 75C (HP 75C) computer. Mathematic rom pack is also used in this programming for this linear regression form.

For the programming, the following processes are applied.

$Ec = \frac{1}{3} aE_fV_f + bE_mV_m$ is converted to the form, $y = ax_1 + bx_2$ just like this formation,

$$y_1 = ax_{11} + bx_{21}$$
$$y_2 = ax_{12} + bx_{22}$$
$$y_3 = ax_{13} + bx_{23}$$
$$\vdots$$
$$y_n = ax_{1n} + bx_{2n}$$

If $X = \begin{bmatrix} x_{11} & x_{21} \\ x_{12} & x_{22} \\ x_{13} & x_{23} \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ x_1n & x_2n \end{bmatrix}$ is, then $Y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \cdot \\ \cdot \\ \cdot \\ yn \end{bmatrix}$ and $C = \begin{bmatrix} a \\ b \end{bmatrix}$

This is also expressed as $Y = XC$ and $X^TY = X^TXC$, which can be converted to the linear regression form of $(X^TX)\text{-}1\,XY = C$ as a matrix.

Table 5 shows the computative results of the programmed. This results indicate that the factors such as density of fiber mat and the amount of matrix used have nothing for affecting the numerical value of the constants a and b of the linear regression form.

Table 5. The constants a and b of the modified rule of mixtures derived from linear regression form

composites \ constant		a	b
rice straw	sulfur + tall oil	3.52	−2.51
	sulfur + polyester	3.54	−2.47
pulp reject	sulfur + tall oil	3.27	−2.80
	sulfur + polyester	3.29	−2.61

4. Conclusions

It is found that the constants a and b applied to the modified rule of mixtures ($Ec = \frac{1}{3} aE_fV_f + bE_mV_m$) are well exploited for the fiber-reinforced sulfur-based composites, no matter what density of fiber mat and amount of matrix used in the composites they have, even though it is natural consequence that different numerical value of constants a and b are given, when different kinds of matrix and fiber species are used.

The direction of further study for the wood-originated, fiber-reinforced composites is to seek as many numerical values of constants a and b as different kinds of fiber and matrix are used in order to establish matrix and fiber species effects on the modified rule of mixtures theorized by Bryant and Lee.

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