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# Creep behavior and manufacturing parameters of wood flour filled polypropylene composites

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**Abstract**

The influence of wood flour content, coupling agent and stress loading level on the creep behavior of wood flour–polypropylene composites was investigated. Maleated polypropylene (MAPP; Epolene G-3003™) was used as the coupling agent to treat the wood flour used as reinforcing filler for polypropylene composite. The tensile strength and modulus of various wood flour–polypropylene composites (WPCs), manufactured using the melt blending, extrusion, and palletizing methods, were measured before performing the creep test. The residual tensile strength, creep strain, and fractional deflection of the resultant wood flour–polypropylene composites were measured by means of the creep test. It was shown that the tensile strength decreased with increasing wood flour level in the composites. The creep strain also decreased as the wood flour level increased. The presence of the coupling agent increased the tensile strength of the wood flour–polypropylene composites, compared with the specimens made of pure polypropylene. For those composites containing the coupling agent, the creep deflection was significantly lower than those made without any coupling agent. The creep strains of the WPC specimens observed during the creep test fitted perfectly with the four-element burger creep model. Further investigation is required of the effects of combined mechanical and environmental loading in varying proportions.


*Keywords:* Wood flour–polypropylene composites; Tensile strength; Residual tensile strength; Maleated polypropylene (MAPP); Creep deflection; Four-element burger creep model

## 1. Introduction

Since the 1970s, studies have been done on the development of new materials which can be used as reinforcing filler, focusing on the potentially advantageous properties of polymers. The need for materials for specific purposes with environmentally friendly characteristics is increasing, due to the limited natural resources and increasing environmental regulation [17,18]. Thus, studies on the development of wood flour–polymer composites (WPCs) using wood flour or natural fiber as reinforcing fillers have been actively pursued [6,12,16]. The wood flour used in WPC in place of the longer individual wood fibers is most often added in particulate form up to the 50% loading level by weight. Although the WPC industry is still only a fraction of a percent of the total wood products industry, the relatively high bulk density and free-flowing nature of wood flours, as well as its low cost and availability, makes it attractive to WPC manufacturers and users [2].

Although most WPC products are considerably less stiff than solid wood, adding wood flour to unfilled plastics can greatly stiffen the plastics, but often makes them more brittle, compared with pure plastics [3,22]. It was reported that coupling agents play an important role in improving the compatibility and bonding strength between the hydrophilic wood fibers and the hydrophobic thermoplastics in WPC [20,10,11]. However, very limited data are available on the relationships between the coupling agent, filler level, stress level, and tensile strength of the wood flour–polymer system in relation to its creep behavior.

Creep is one of the principal properties which needs to be addressed when developing and using composite

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materials. It was reported that most materials respond differently depending on the time required to complete the mechanical test [13]. The deflection of materials under short- and long-term loading is sometimes critical to their performance. The time-dependent stress–strain behavior of composites is particularly important. Since WPCs can be subjected to mechanical loadings over extended periods of time, measuring their short-term tensile strength and stiffness may not be sufficient to provide the information required to predict their long-term performance [8]. For situations involving a higher load-carrying capacity, however, an understanding of the short-term mechanical response of newly designed materials may be required.

Models can be helpful for both the interpretation and prediction of the observed creep behavior. Although mathematical expressions which fit to the experimental data offer no guarantee that the equations are valid for any conditions other than the ones described, this problem can be partially overcome by demonstrating that the real behavior is consistent with that of the model. Among the available creep models, the four-element burger body has many advantages for the prediction of creep behavior due to the insertion of the Kelvin body between the spring and dash spot of the Maxwell body (Fig. 1). The sequence shown in Fig. 1 illustrates both the deformation and recovery stages. At time $t_0$, the four-element model is of length $L$. At time $t_1$, load $P$ is applied and an immediate elastic deformation, $u_e$ results from the elongation of the upper spring. At time $t_2$, the burger diagram body has extended to a total deformation, $u$. At time $t_3$, the load is removed. The spring, $k_e$, contracts instantaneously, reducing the total deformation by $u_e$ At time $t_4$, the deformation, $u_v$ of the Kelvin body is approaching zero. Finally, a residual deformation, $u_v$ remains in the viscous element. The mathematical model is expressed by the following equation [9]:

$$\begin{aligned}\varepsilon(t) &= \varepsilon_e + \varepsilon_k + \varepsilon_v \\ &= \sigma/K_e + [\sigma/K_k][1 - e^{(-K_k t/\eta_k)}] + \sigma t/\eta_v \qquad (1)\end{aligned}$$

where $\varepsilon(t)$ is the total creep strain, $\varepsilon_e$ the elastic strain, $\varepsilon_k$ the viscoelastic strain, $\varepsilon_v$ the viscoplastic strain, $\sigma$ the applied stress, $K_e$ the elastic constant of the Hookean spring, $K_k$ the delayed elastic constant of the spring element in the Kelvin body, $\eta_k$ the viscous constant of the damper in the Kelvin body, and $\eta_v$ is the viscous constant for the permanent deflection.

The objectives of this study were: (1) to investigate the influence of the wood flour and coupling agent on the mechanical properties of wood flour–polypropylene (PP) composites, (2) to measure the creep properties under indoor conditions, and (3) to find a mathematical model which fits with the observed creep behavior.

## 2. Materials and methods

### 2.1. Sample preparation

The wood flour used as a reinforcing filler was obtained from a mixed wood species courtesy of the Korea Forest Research Institute, South Korea. The particle sizes of the filler were 80–100 mesh. PP was obtained from HANWHA L&C Corp., South Korea. The PP was supplied in the form of homopolymer pellets with a melt flow index of 12 g/10 min (230 °C/2, 160 g) and a density of 0.91 g/cm$^3$. A maleated polypropylene (MAPP; commercial name is Epolene G-3003™, Eastman

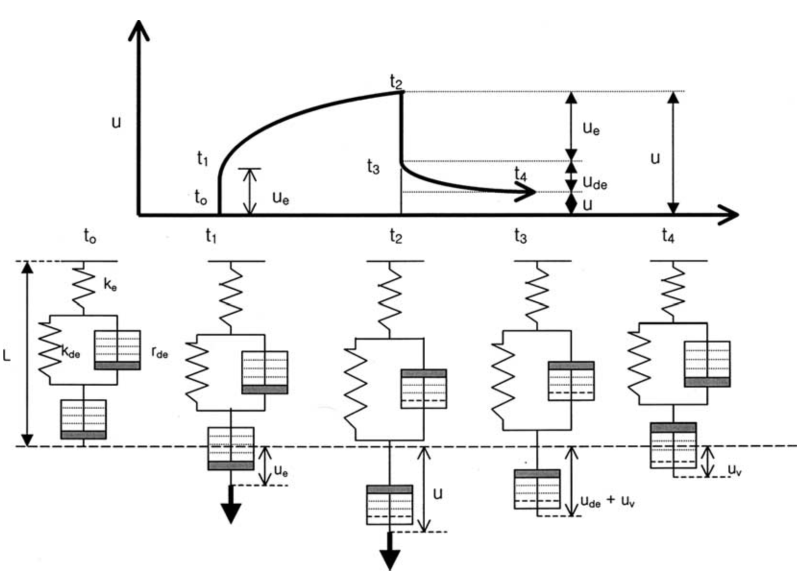


Fig. 1. Four-element burger body diagram of creep behavior.

chemicals Co. Ltd.) was used as the coupling agent in this study. Epolene G-3003™ has a number-average molecular weight of 103,500 and a low acid number of 8.

### 2.2. Compounding

The wood flour was dried to 1–2% moisture content using an oven drier at a temperature of 80 °C for 24 h, and then stored in polyethylene bags until needed. The laboratory size extruder was a twin-screw type which blends thermoplastic composites reinforced with wood flour, through the following three general processes—melt blending, extrusion and palletizing. The blending temperature required to prevent degradation of the wood flour was 190 °C. The extrudate, which was in the form of strands, was cooled in water and palletized. The resulting pellets were dried at 80 °C for 24 h before being injection molded into ASTM test specimens (ASTM D638 2000) [1]. All materials were injection molded using an injection-molding machine (Bau Technology, South Korea). The wood flour application levels were 0%, 10%, 20%, 30% and 40%, based on the total weight, prior to compounding. The corresponding rates of PP were 100, 90, 80, 70 and 60 wt.%. The application level of Epolene G-3003™, which was used as a coupling agent, was 3.0% based on the total weight of the wood flour and PP.

### 2.3. Short-term tensile strength

Single tensile tests for the WPC were conducted to measure the short-term strengths according to the ASTM Standard Test Method (ASTM D638 2000) [1] with a Universal Testing Machine (Zwick Co., NICEM at Seoul National University). Test specimens for the evaluation of tensile strength were molded in a mold whose cavity had the following dimensions: $W = 3.18 \pm 0.03$ mm, $L = 9.53 \pm 0.08$ mm, $G = 7.62 \pm 0.02$ mm, $T = 3.00 \pm 0.08$ mm, where $W$ is the width of the narrow section, $L$ the length of the narrow section, $G$ the gage length, and $T$ is the thickness of the narrow section. The tests were conducted on samples with an initial length of 63.5mm using a universal tensile test device at a speed of 100 mm/min. This device was used for the evaluation of the tensile strength, from which the stress levels were determined for the constant load used for the creep testing. Each test condition was repeated 5 times to obtain more representative results.

### 2.4. Creep test

Specimens with the same size as the tensile test specimens were chosen with five different filler levels (0, 10, 20, 30 and 40 wt.%), and two different applied stress levels (20% and 40% of tensile strength). Fig. 2 shows a schematic diagram of the creep tester. Each sample was attached to the loading device using a clamping system composed of a steel bar with nuts and bolts. The time period used for the creep test was kept constant at 6 h, and was followed by 1 h-recovery at a temperature of 25 °C. The actual stresses applied to the specimens are listed in Table 1. Strain was applied during the creep test by means of a linear variable differential transducer (LVDT), as the signals were collected using a data acquisition unit. The LVDT was directly linked to the clamp and the dial gauges were attached at the mid-point of the samples to inspect the slippage between the sample and the clamp. The load was applied using a compressed steel weight. After the specimens had recovered from the creep test, they were tensile-tested for the evaluation of their residual strength and stiffness.

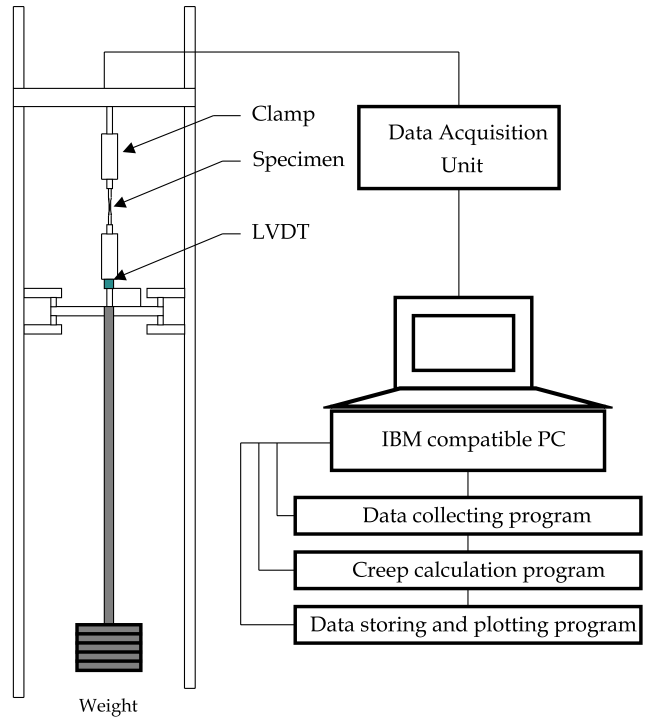


Fig. 2. Schematic diagram of creep test apparatus.

### 2.5. Creep data processing

Tensile creep data processing was performed with Microsoft Excel running on the Work Bench PC by means of a dynamic data exchange tool (Fig. 2). Fractional deflection is usually used as a relative measure of creep performance, which allows cross comparison of groups with different filler levels and the addition of coupling agent. For the investigation of the constant load short-term creep of a given WPC, the fractional deflection was determined by a following equation:

$$F_{\rm d} = C_i/C_0 \tag{2}$$

Table 1
The tensile strength and modulus of the WPC specimens as a function of the filler loading, with and without the coupling agent, before and after the creep test

| | Wood flour (%) | No CA[a] ($N/mm^2$) | CA[a] ($N/mm^2$) | 20% SL[b] ($N/mm^2$) | 40% SL[b] ($N/mm^2$) | 20% SL–CA[b] ($N/mm^2$) | 40% SL–CA[b] ($N/mm^2$) |
|---|---|---|---|---|---|---|---|
| Tensile strength | 0 | 38.06 a | N/A | 37.80 a | 37.85 a | N/A | N/A |
| | 10 | 37.06 b | 40.70 a | 37.90 a | 37.95 a | 40.05 a | 40.60 a |
| | 20 | 36.88 b | 44.10 b | 36.55 b | 36.65 b | 45.00 b | 44.95 b |
| | 30 | 36.18 b | 48.34 c | 36.05 b | 36.40 b | 49.10 c | 48.15 c |
| | 40 | 34.56 c | 51.66 d | 34.45 c | 35.00 c | 51.90 d | 52.10 d |
| Tensile modulus | 0 | 45.62 | N/A | 26.90 | 36.1 | N/A | N/A |
| | 10 | 40.18 | 44.70 | 27.95 | 35.6 | 40.00 | 36.2 |
| | 20 | 38.66 | 46.76 | 31.30 | 35.55 | 35.55 | 35.75 |
| | 30 | 35.44 | 46.36 | 32.40 | 33.35 | 37.10 | 41.75 |
| | 40 | 33.96 | 44.73 | 37.65 | 34.95 | 42.60 | 42.1 |

[a] Each value of the tensile strength and modulus before the creep test represents the mean of five replicate experiments for the wood flour–PP composites.
[b] Each value of the tensile strength and modulus after the creep test represents the mean of two replicate experiments for the wood flour–PP composites. Those means within the same column which are followed by the same letter are not significantly different (ANOVA, Tukey's studentized-range test, $\alpha = 0.05$).

where $F_d$, $C_i$, and $C_0$ are the fractional deflection during the period $i$, the creep deflection during the period $i$ (mm), and the instantaneous deflection (mm).

The relationship between stress and strain was defined by the one-dimensional Hooke's law. Once the creep strain mode was obtained as a function of time, the nonlinear curve fitting technique was employed to determine the creep model parameters using the four-element burger body model described in Eq. (1). The prediction of the strain induced during an extended period was carried out by plugging the parameters into Eqs. (1) and (2).

### 2.6. Data analysis

A regression analysis was performed to establish the correlation between the wood flour level and the coupling agent. Statistical comparisons, based on three-way ANOVA, were performed to test the effects of wood flour level, coupling agent, and stress level, and their interactions on the creep properties. Tukey's studentized-range test at the 5% significance level was used to compare the differences among the mean values resulting from the different treatments [21].

## 3. Results and discussion

### 3.1. Short-term tensile strength

The tensile strengths of the WPC specimens were measured by means of a universal tensile test device (Table 1). Fig. 3 shows the relationship between the tensile strength and the filler loading with and without the coupling agent. The maximum tensile strength of the WPC specimens without any coupling agent was 38.06 $N/mm^2$. It was found that the tensile strength decreased with increasing filler loading (wt.%) of the composites. The addition of 40 wt.% wood flour resulted in a decrease in strength of approximately 9.2%, compared with the pure PP. A similar result was reported in a previous study, in which the addition of 20 wt.% wood flour to PP gave rise to a 9.5% strength reduction compared with pure PP [19]. The tensile strength reduction was linearly fitted by regression ($R^2 = 0.9205$) as a function of the filler loading. This result may be attributed to the decrease of bonding strength between the wood flour and the PP, because most polymers, especially thermoplastics, are non-polar (hydrophobic) substances that are not compatible with polar (hydrophilic) wood flour [7,10].

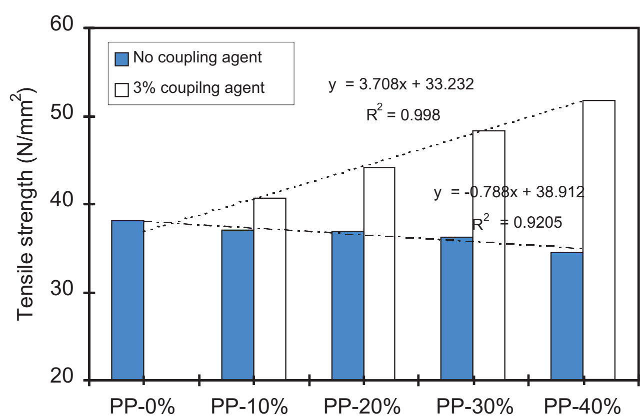


Fig. 3. The relationship between tensile strength and filler loading with and without the coupling agent (Epolene G-3003™). $R^2$ indicates the coefficient of determination by linear regression.

The maximum tensile strength of the WPC specimens with coupling agent was 51.66 $N/mm^2$ at the 40 wt.% wood flour level (Table 1). The addition of the coupling agent significantly increased the tensile strength, compared with the pure PP specimens (Fig. 3). The tensile strength increment was linear fitted by a regression ($R^2 = 0.9980$). This result is totally different from that of the specimens without any coupling agent. The tensile strength at 40 wt.% filler loading was 51.7% higher than that of the pure PP specimens, because of the increased bonding strength between the wood flour and the PP as compared to the intermolecular bonding of pure PP itself. It was reported that MAPP has also been employed to provide compatibility between immiscible polymers through the reduction of the interfacial tension [14].

The results of the one-way ANOVA indicated that the differences among the treatment means were significant at the 5% significance level ($\Pr \leqslant 0.0001$). The filler loading had a highly significant effect on the tensile strength of the wood flour–PP composites.

### 3.2. Stress–strain behavior before and after creep test

The stress–strain curves of the composites, with and without coupling agent, at different filler loadings are shown in Fig. 4(a)–(d). As shown in Fig. 4(a), the WPC specimens exhibited more brittleness as the filler loading increased [3]. In addition, the bonding at the interface became increasingly weak with increasing filler loading. The tensile modulus improved with increasing filler loading, which is in total agreement with previous studies [4,5]. It is generally considered that poor bonding strength results from the formation of micro-voids between the wood flour and the polymer matrix, which interferes with the stress distribution during the tensile test.

The stress–strain curves of the composites with coupling agent at different filler loadings are shown in Fig. 4(b). When Epolene G-3003™ was added at a level of 3 wt.%, the tensile strength and modulus of the composite improved [15]. The composite began to exhibit more brittle fractures with the addition of the coupling agent. The coupling agent lowers the surface energy of the wood flour and makes it non-polar, and therefore more like the matrix polymer. It is believed that the improved interfacial bonding between the filler and the matrix polymer, due to

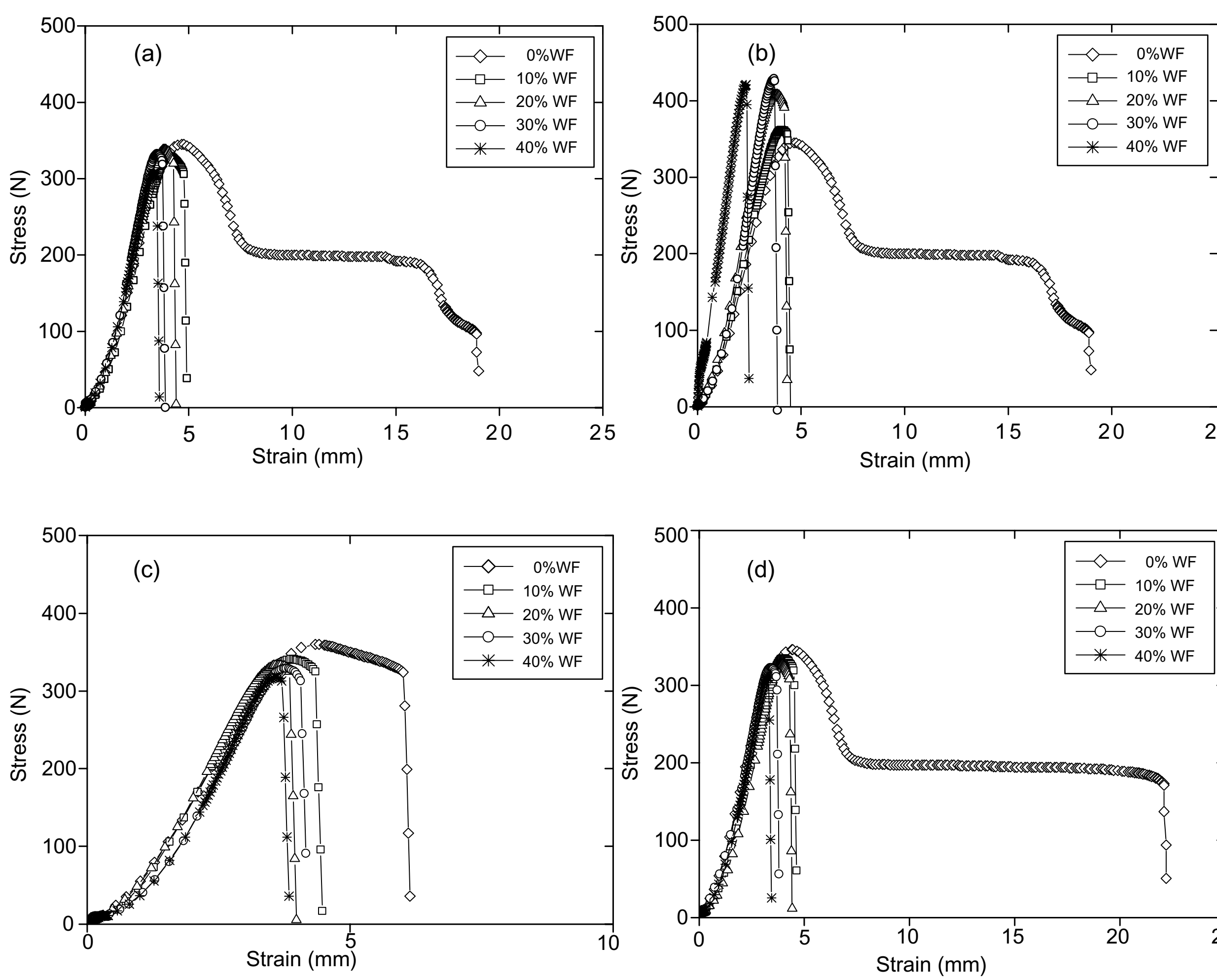


Fig. 4. The stress–strain curves of the WPC: (a) no creep and no coupling agent; (b) no creep and coupling agent; (c) creep and no coupling agent and (d) creep and coupling agent. WF indicates the wood flour level.

the presence of the coupling agent, resulted in better stress propagation and improved the tensile strength.

The stress–strain curves obtained after the creep test, with and without the coupling agent, showed the same tendency as that exhibited by the composites before the creep test [Fig. 4(c) and (d)]. However, the composites showed lower strain values after the creep test than before the creep test. From this result, it is assumed that creep behavior lowers the resistance of the composite against tensile stress. On the other hand, the strains of the composites with different wood flour levels before the creep test showed a similar strain tendency after the creep test, regardless of whether or not the coupling agent was present. It was found that neither the tensile strength nor the modulus were affected by the level of creep loading, when wood flour is added. This indicates that the micro-voids between the filler and the matrix polymer which developed under tensile loading recovered as the loading was released.

### 3.3. Creep behavior of the control groups

A few representative curves for the control groups are illustrated in Fig. 5, the summary of the creep test results in Table 2, and the results of the statistical analyses in Table 3. A slight variation in creep deflection was observed in all of the control groups in most creep stages. Relatively large maximum creep deflections (1.853–2.977 mm/mm) were obtained from 6 h constant loading, considering that this constitutes a relatively short testing span (2.5 cm). The creep responses of the two groups, loaded at the stress levels of 20% and 40%, varied considerably both in the presence and absence of coupling agent (Epolene G-3003™). The instantaneous and maximum creep deflections at the 40% stress level were significantly higher (3.5 times at 6 h loading) than those at the 20% stress level. It was found that the creep deflection showed a significant relationship with the stress level under creep loading.

### 3.4. Effect of wood flour level

The creep curves and deflections obtained from the WPC specimens under creep loading at the different wood flour levels were compared with the controls, and the results are shown in Fig. 5(a) and (b) and Table 2. It is apparent that the effect of the wood flour was highly significant. In general, however, the creep strain decreased as the wood flour level increased. This implies that the decrease in creep strain resulting from the addition of the wood flour is inversely related to the increase in brittleness. The creep strain of the specimens with 10 wt.% filler loading at the 40% stress level was lower than that of the control group and was much higher that of the specimens with 20 wt.% filler loading (Table 2 and Fig. 5(a)). However, the creep strains of the

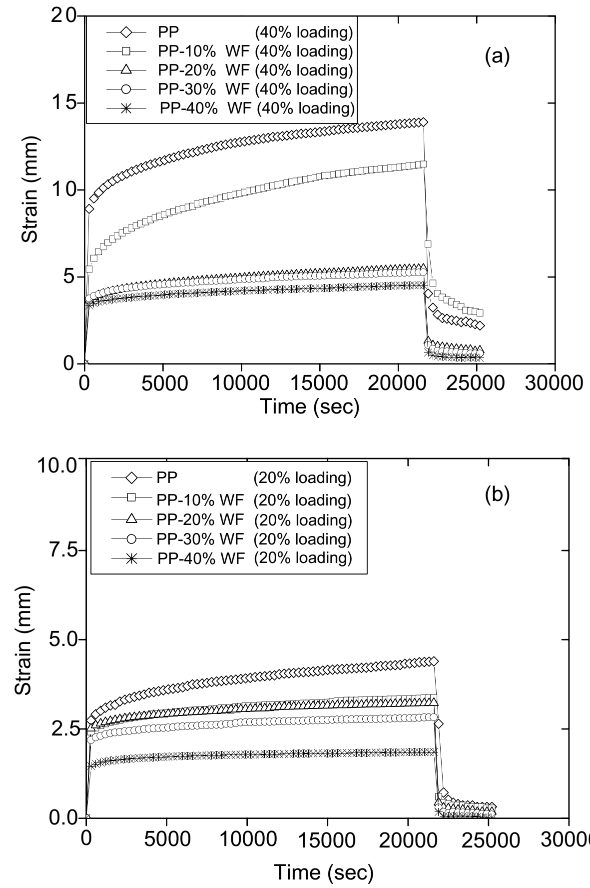


Fig. 5. The effects of wood flour application level on creep behavior of WPC without any coupling agent (Epolene G-3003™): (a) 40% stress level and (b) 20% stress level.

specimens with between 20 and 40 wt.% filler loading at the 40% stress level showed similar creep behavior. However, the creep strains of the specimens with wood flour contents of up to 40 wt.% at the 20% stress level were relatively lower than those at 40% stress level [Fig. 5(b)]. After relaxation from the constant loading, the instantaneous recovery and permanent deflection at the 40% stress level decreased as the wood flour level increased [Fig 5(a)]. However, the instantaneous recovery and permanent deflections at the 20% stress level were almost the same, even though the wood flour levels increased [Fig. 5(b)]. However, the difference in creep deflection between the control and WPC specimens may be amplified when the loading period is extended. From the results, it is believed that the addition of wood flour has a positive effect on the creep behavior. Therefore, the addition of wood flour provides a way of increasing the cost effectiveness of the WPC, because wood flour is less expensive than thermoplastic materials.

### 3.5. Effect of coupling agent

As shown in Fig. 6(a) and (b), one peculiar difference found between the two stress levels was the variation of

Table 2
Creep deflection data for each WPC group

| WF[a] (%) | CA[b] (%) | LD[c] (% MOR) | Instantaneous deflection (mm) | Maximum deflection (mm) | Fractional deflection[d] (mm/mm) | Instantaneous recovery (mm) | Permanent deflection (mm) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 20 | 0.571 | 1.101 | 1.928 | 0.806 | 0.144 |
| 10 | 0 | | 0.509 | 0.844 | 1.658 | 0.694 | 0.035 |
| 20 | 0 | | 0.553 | 0.809 | 1.463 | 0.744 | 0.045 |
| 30 | 0 | | 0.474 | 0.708 | 1.494 | 0.633 | 0.025 |
| 40 | 0 | | 0.318 | 0.464 | 1.459 | 0.459 | 0.010 |
| 10 | 3 | 20 | 0.364 | 0.712 | 1.956 | 0.616 | 0.030 |
| 20 | 3 | | 0.376 | 0.696 | 1.851 | 0.596 | 0.030 |
| 30 | 3 | | 0.333 | 0.566 | 1.699 | 0.512 | 0.020 |
| 40 | 3 | | 0.300 | 0.468 | 1.560 | 0.431 | 0.010 |
| 0 | 0 | 40 | 0.962 | 2.864 | 2.977 | 1.102 | 0.725 |
| 10 | 0 | | 0.972 | 1.759 | 1.810 | 1.036 | 0.385 |
| 20 | 0 | | 0.766 | 1.374 | 1.794 | 0.522 | 0.115 |
| 30 | 0 | | 0.807 | 1.318 | 1.633 | 1.038 | 0.160 |
| 40 | 0 | | 0.731 | 1.133 | 1.550 | 0.447 | 0.080 |
| 10 | 3 | 40 | 0.910 | 1.686 | 1.853 | 1.244 | 0.260 |
| 20 | 3 | | 0.700 | 1.272 | 1.817 | 0.963 | 0.180 |
| 30 | 3 | | 0.569 | 1.006 | 1.768 | 0.811 | 0.115 |
| 40 | 3 | | 0.520 | 0.833 | 1.602 | 0.633 | 0.085 |

[a] WF: wood flour levels (0, 10, 20, 30 and 40 wt.%).
[b] CA: coupling agent (3 wt.% Epolene G-3003™).
[c] LD: loading level (20% and 40% tensile stress).
[d] Fractional deflection $= C_i/C_0$, where $C_i$ and $C_0$ are $i$th creep deflection and instantaneous creep deflection, respectively.

Table 3
Results of statistical analysis for creep performance of wood flour–PP composites tested ($\alpha = 0.05$)

| CA | Factor | Instantaneous deflection ($\Pr > F$) | Maximum deflection ($\Pr > F$) | Fractional deflection ($\Pr > F$) | Instantaneous recovery ($\Pr > F$) | Permanent deflection ($\Pr > F$) |
|---|---|---|---|---|---|---|
| N/A | WF[a] | <0.0001 | <0.0001 | 0.0001 | 0.0232 | 0.0001 |
| | LD[b] | <0.0001 | <0.0001 | <0.0001 | 0.0844 | <0.0001 |
| | WF × LD[c] | 0.0008 | <0.0001 | 0.0025 | 0.1684 | 0.0025 |
| 3% | CA[d] | <0.0001 | <0.0001 | <0.0001 | 0.6067 | 0.4527 |
| | WF | <0.0001 | <0.0001 | <0.0001 | 0.0010 | 0.0023 |
| | LD | <0.0001 | <0.0001 | 0.0065 | 0.0003 | <0.0001 |
| | CA × WF | 0.0010 | 0.1055 | 0.6203 | 0.2328 | 0.4577 |
| | CA × LD | 0.0839 | 0.0179 | 0.0185 | 0.0419 | 0.6504 |
| | WF × LD | <0.0001 | <0.0001 | 0.5975 | 0.0489 | 0.0073 |
| | CA × WF × LD | <0.0001 | 0.0045 | 0.1746 | 0.2175 | 0.3925 |

[a] WF: wood flour level (0, 10, 20, 30 and 40 wt.%).
[b] LD: loading level (20% and 40% tensile stress).
[c] A × B: interaction effect between A and B.
[d] CA: coupling agent (3 wt.% Epolene G-3003™).

creep deflection caused by the presence of Epolene G-3003™. With the coupling agent, the creep deflection was approximately two times lower than that without any coupling agent at the 40% stress level (Table 2). As a result, it is assumed that Epolene G-3003™ improved the creep resistance. The creep deflection significantly decreased as the wood flour level increased. It is believed that the coupling agent improves the compatibility between the wood flour and the thermoplastic polymer up to a wood flour level of 40 wt.%. As shown in Fig. 6, the creep strain with the coupling agent at the 20% stress level was also significantly lower (1.2–1.5 times) than that without the coupling agent (Table 2). However, the creep strains of the specimens with and without coupling agent at the 20% and 40% wood flour level were similar to each other. The difference of creep strain between the composite with and without the coupling agent decreased as the wood flour level increased. There may be

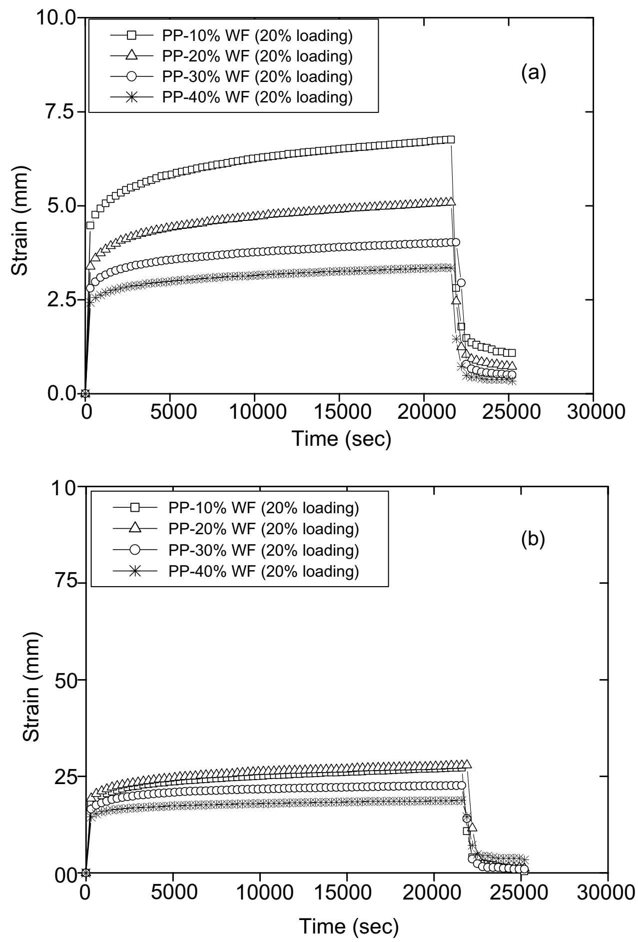


Fig. 6. The effects of wood flour application level on creep behavior of WPC with and without any coupling agent (Epolene G-3003™): (a) without any coupling agent and (b) with Epolene G-3003™.

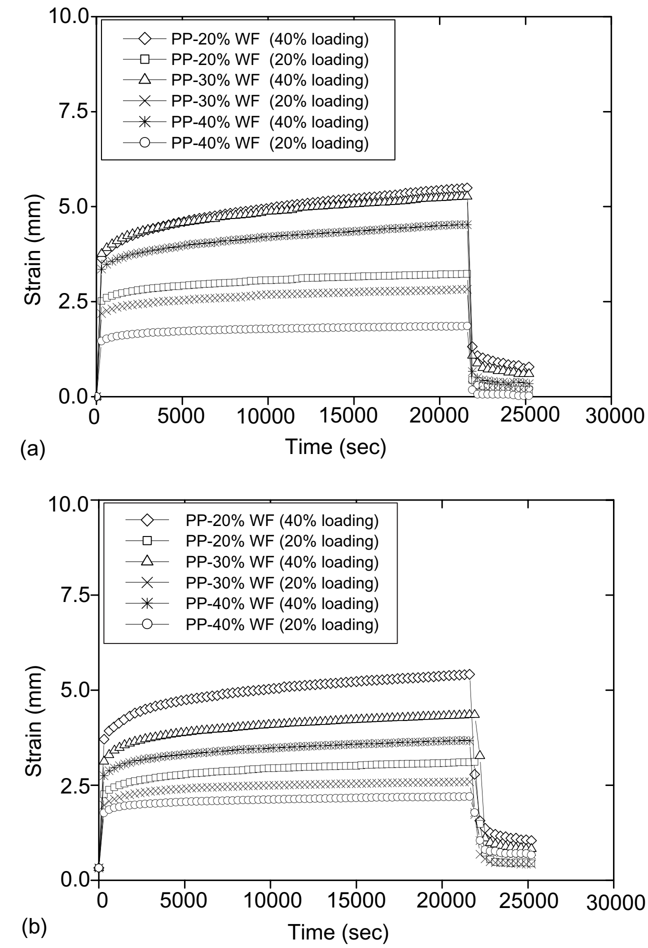


Fig. 7. The effects of stress level on creep behavior of WPC: (a) without any coupling agent and (b) coupling agent (Epolene G-3003™).

an interactive effect between the wood flour level, the presence or not of the coupling agent, and the stress level.

### 3.6. Effect of stress level

A significant difference in creep behavior was observed between the groups loaded at stress levels of 20% and 40%, as shown in Fig. 7(a) and (b) and Table 2. The groups loaded at the 20% stress level exhibited a little increase in creep deflection after 6 h loading than those loaded at the 40% stress level, as indicated by the fractional deflection. This can be seen more clearly by examining the difference in creep deflection between the two stress levels presented in the following manner: 1.928, 1.463, and 1.459 mm at the 20% stress level and 2.977, 1.794, and 1.550 mm at the 40% stress level with wood flour levels of 0, 20 and 40 wt.%, respectively.

According to the three-way ANOVA (Table 3), varying the wood flour content and stress level had a highly significant effect on the creep behavior (especially maximum deflection) of the WPC with and without any coupling agent at the 5% significance level. The interaction effects between the wood flour and stress level were also significant. On the other hand, the main effect of Epolene G-3003™ on the creep behavior of WPC with different wood flour contents and stress levels was also significant. The main effects of the wood flour content and stress level on the creep properties were highly significant. Except for the interaction effects of the coupling agent and wood flour content, all interaction effects on the creep properties were highly significant. The results shown in Figs. 5–7 were confirmed by this statistical analysis using ANOVA.

### 3.7. Fractional deflection

The fractional deflection of the WPC specimens is illustrated in Fig. 8 and the results of the statistical analysis of the effect of wood flour content and stress level on fractional deflection are summarized in Table 3. The effects of wood flour content and stress level on the fractional deflection were clearly observed, both with

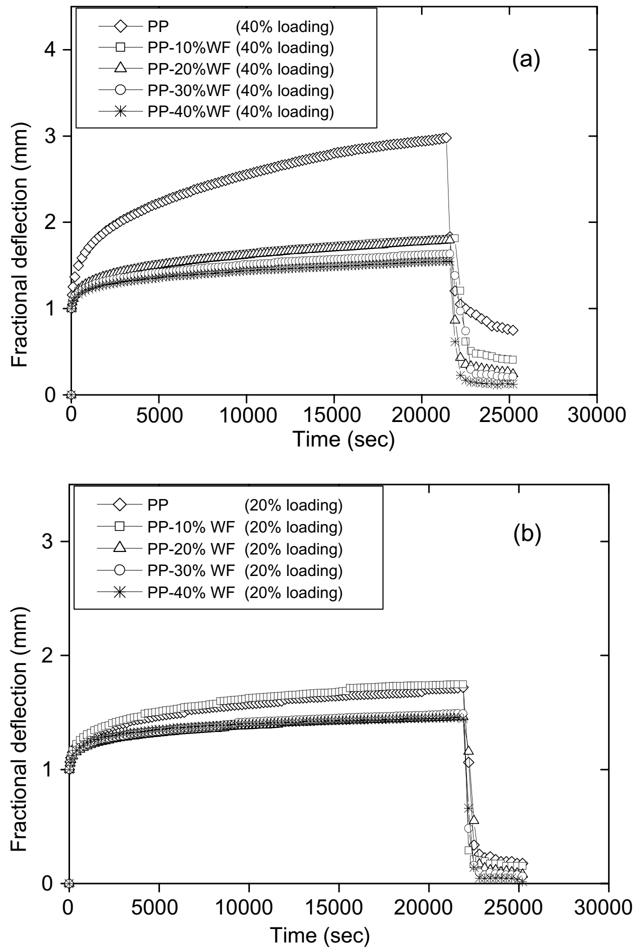


Fig. 8. Fractional deflection of WPC: (a) 40% stress level and (b) 20% stress level.

and without the coupling agent. It appeared as though the presence of the wood flour and the applied stress contributed to the decrease of fractional deflection for a given set of conditions. The interaction effect between the wood flour content and the stress level, in the absence of the coupling agent, had a significant effect on the fractional deflection, but this effect was not significant in the presence of Epolene G-3003™.

In both the groups with and without coupling agent, the values of fractional deflection for the specimens loaded at the 40% stress level were somewhat larger than those of the specimens loaded at the 20% stress level, as shown in Table 2. This might be because those groups loaded at the 40% stress level had a larger instantaneous deflection than those loaded at the 20% stress level. The lowest fractional deflection (1.459 mm/mm) was observed at the 40 wt.% wood flour level without any coupling agent and the highest (2.977 mm/mm) was found in the specimens with a 0% wood flour level without any coupling agent.

### 3.8. *Effect of creep on residual tensile properties*

The effect of creep on the residual tensile strength was not significant, as shown in Table 1. In general, the tensile strength after the creep test was almost the same as that before the creep test. The WPC specimens without any coupling agent showed a reduction in tensile strength in the groups loaded at the 20% and 40% stress level. However, the stress level had no influence on the residual tensile strength. The residual tensile modulus was not affected by the creep test. As shown in Table 1, a large variation was observed after the creep test. Six hour duration under tensile creep had no significant effect on the load-carrying capacities of the WPC specimens. It is believed that all of the deformation caused by creep loading was recovered after relaxation.

Table 4
Creep parameters of burger body model of WPC with and without the coupling agent at different wood flour levels and stress levels

| Stress level | Parameters | Coupling agent | Wood flour level (wt.%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 10 | 20 | 30 | 40 |
| 20% | $K_e$ (MPa) | N/A | 2.710 | 2.408 | 2.523 | 2.199 | 3.339 |
| | $K_k$ (MPa) | N/A | 0.846 | 0.513 | 0.411 | 0.368 | 0.566 |
| | $\eta_k$ ($10^{-3}$ MPa s) | N/A | 0.368 | 0.380 | 0.326 | 0.309 | 0.410 |
| | $\eta_v$ ($10^{-5}$ MPa s) | N/A | 3.884 | 2.173 | 1.420 | 1.210 | 3.000 |
| 40% | $K_e$ (MPa) | N/A | 8.974 | 5.538 | 3.605 | 3.725 | 1.444 |
| | $K_k$ (MPa) | N/A | 3.015 | 3.172 | 0.902 | 0.787 | 0.269 |
| | $\eta_k$ ($10^{-3}$ MPa s) | N/A | 0.296 | 0.280 | 0.409 | 0.400 | 0.510 |
| | $\eta_v$ ($10^{-5}$ MPa s) | N/A | 9.117 | 13.351 | 4.651 | 4.000 | 6.800 |
| 20% | $K_e$ (MPa) | 3% | N/A | 1.754 | 1.919 | 1.609 | 1.419 |
| | $K_k$ (MPa) | 3% | N/A | 0.559 | 0.552 | 0.471 | 0.294 |
| | $\eta_k$ ($10^{-3}$ MPa s) | 3% | N/A | 0.547 | 0.402 | 0.531 | 0.661 |
| | $\eta_v$ ($10^{-5}$ MPa s) | 3% | N/A | 1.968 | 1.460 | 0.889 | 0.796 |
| 40% | $K_e$ (MPa) | 3% | N/A | 4.429 | 3.321 | 2.757 | 2.393 |
| | $K_k$ (MPa) | 3% | N/A | 1.400 | 1.049 | 0.756 | 0.567 |
| | $\eta_k$ ($10^{-3}$ MPa s) | 3% | N/A | 0.391 | 0.457 | 0.500 | 0.478 |
| | $\eta_v$ ($10^{-5}$ MPa s) | 3% | N/A | 4.424 | 3.439 | 2.449 | 1.898 |

### 3.9. Modeling viscoelastic creep strain

The parameters utilized in the four-element burger body creep model are listed in Table 4. As shown in Fig. 9(a)–(d), the model perfectly predicted the creep strain of the WPC specimens during the entire set of creep tests. The observed decreases of creep strain due to the wood flour, stress level, and Epolene G-3003™ were accurately predicted by the model. $K_e$, the equivalent modulus of elasticity, was in the range of 1.419–8.974 MPa. Those groups with Epolene G-3003™ showed relatively lower values of $K_e$ at the 20% and 40% stress levels. As the wood flour content increased, $K_e$ decreased for both the groups with and without coupling agent. $K_k$, the delayed elastic constant of the spring element in the Kelvin body, increased with increasing stress level, but there was no significant relationship between the wood flour level and $K_k$. Higher values of $K_k$ were given by the addition of Epolene G-3003™. The other two parameters were also higher in the presence of Epolene G-3003™, but there was no significant relationship with the wood flour level. These results are consistent with the above discussion concerning the creep deflection.

## 4. Conclusion

The tensile strength of the composites decreased with increasing filler loading, due to the resulting decrease in bonding strength between the wood flour and the PP. The addition of Epolene G-3003™ increased the tensile strength, compared with pure PP, because it improved the compatibility between the wood flour and PP, by reducing the interfacial tension. The effect of the wood flour content on creep was highly significant. The creep strain decreased as the wood flour level increased, due to the resulting increase in brittleness. With Epolene G-3003™, the creep deflection was approximately two

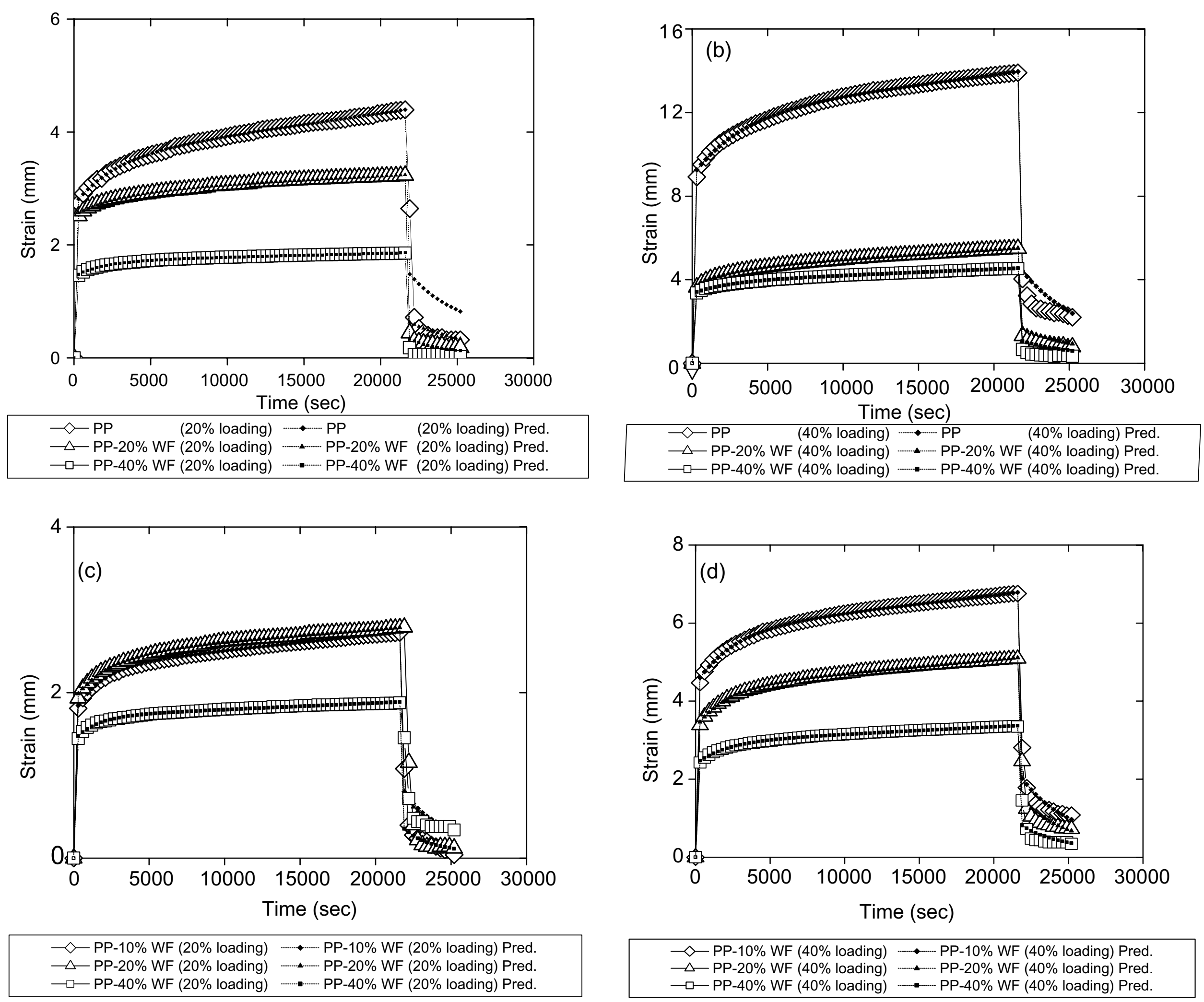


Fig. 9. Observed strain and strain predicted by the four-element burger body creep model for WPC. Without any coupling agent ((a) and (b)) and with coupling agent ((c) and (d)).

times lower than that without the coupling agent. Epolene G-3003™ improved the compatibility between the wood flour and the matrix polymer. Those groups loaded at the 20% stress level showed a lower increase in creep deflection than those loaded at the 40% stress level. The effect of creep on the residual tensile strength was not significant. The tensile strength after the creep test was almost the same as that before the creep test. This implies that the micro-voids between the wood flour and the matrix polymer under tensile loading recovered when the loading was released. The four-element burger body creep model perfectly predicted the creep strain of the WPC specimens for the entire set of creep tests. The decreases in creep strain due to the wood flour, stress level, and Epolene G-3003™ were accurately predicted by the model.

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