Effect of CO₂ on the degradation of cement-bonded particleboard based on the treatment to conventional cured board

R S Maail
Department of Forest Products Technology, Faculty of Agriculture Pattimura University, Jl. Ir. M. Putuhena, Ambo, Indonesia
e-mail: rohny_maail@yahoo.com

Abstract. This study aimed to evaluate and clarify the effect of CO₂ at either the gaseous or supercritical phase on the degradation of cement-bonded particleboard (CBP) based on the treatment to conventional cured board, while the estimation of long term degradation of CBP is also discussed. The properties of CBP are improved by CO₂ treatment in short period in both the gaseous and supercritical phases even after the conventional curing process. These properties, however, over the longer treatment time degraded in rapid rate against CO₂ treatment in both the gaseous and supercritical phases. It was considered that the degradation of CBP increased with increasing the CO₂ concentration, CO₂ pressure and treatment time. With the longer treatment time against supercritical CO₂ in higher concentration and pressure, the residual values of mechanical properties (IB strength, MOR, and MOE) were decreased, indicating CBP performance was degraded rapidly compared to treatment in the lower concentration and pressure of CO₂ or under gaseous phase. High coefficient determination values between the residual values of CBP properties, and the treatment time and CO₂ concentration were observed and the simple linear model was found to estimate the long term degradation of CBP among the properties and affecting factors.

1. Introduction
A well-known phenomenon associated with cement-based materials placed in natural environmental locations is the carbonation that occurs naturally over numerous years owing to the reaction with atmospheric CO₂.¹ The carbonation process occurs rather slowly in natural environment due to the low concentration of CO₂ in the environment which is only 0.03-0.04% by volume. Most of the work carried out on the carbonation of cementation materials have been concentrated in the variation of the microstructure and mechanical properties in contact with CO₂ as a function of the type of cement being used for the concrete or cement composites. Different authors²⁴ have investigated the effects of carbonation on pore structure, changes of specific surface area, permeability, and diffusion properties of hydrated cement pastes and mortars as the degradation process. The variations of different properties i.e., the permeability, porosity, and pore size distribution as a consequence of the carbonation process in cement-based materials [5-7]. Additionally a few comparative studies on carbonation have been carried out on cement samples, resulting that microstructure of cement paste carbonated using supercritical CO₂ was different than that of natural-carbonated paste. The depth of carbonation in real environmental condition was estimated based on the result obtained from the accelerated carbonation test on the fly ash and blast-furnace slag concrete [8].
The carbonation is also one of the major causes of degradation of cement-bonded particleboard (CBP) over the time due to contact with CO₂. This phenomenon was clarified in our previous study, in which CO₂ in a supercritical phase accelerates the curing process and enhances the mechanical properties of CBP in the short treatment time, however, in the longer time span leads to degradation in mechanical properties because of the carbonation of cement, resulting negative effect on board performance. In the experimental works, data about the long-term performance of CBP are scarce. Therefore, in the present study, it is desirable to accelerate the carbonation process to shorten the duration of treatment time to predict long term performance of CBP. The acceleration can be performed either by increasing the concentration or the pressure of CO₂. Although many studies on manufacturing CBP using CO₂ in either setting or curing process at both the gaseous and supercritical phase have been done, none has clarified the estimation of degradation process of CBP based on the result obtained from CO₂ treatment to conventional cured board, beside the literatures concerned with the analysis of carbonation which is affected to the degradation of CBP at elevated pressures and concentration of CO₂ are less common. It was then possible to observe the degradation of CBP by measuring the residual values of CBP properties based on the degradation values of CBP properties treated at both the gaseous and supercritical CO₂ phases in certain period.

The objectives of this study were to evaluate and clarify the effect of CO₂ at either the gaseous or supercritical phase on the degradation of CBP based on the treatment to conventional cured board and the results were applied to estimate long term degradation of CBP by applying the equation models from statistical method and analysis.

2. Materials and methods

2.1 Materials
Mixtures with proportionally equal amounts of particles of Japanese cypress (Chamaecyparis obtusa Endl) and Japanese cedar (Cryptomeria japonica D.Don) were used to manufacture CBP. The average size of the wood particles was 3.3 mm (L), 0.7 mm (W), and 0.1 mm (T). Ordinary Portland cement of Osaka Sumitomo Co. Ltd. was used as a binder; CO₂ was used as an accelerator for curing and carbonation processes at either the gaseous or supercritical phase. To produce supercritical CO₂, CO₂ gas was maintained in the liquid phase by passing the gas through a condenser. The liquid CO₂ was then pumped into the reaction cell surrounded by a water jacket set at 40°C at a pressure up to 10 MPa.

2.2 Manufacture and treatment of CBP
CBP with a targeted density of 1.2 g/cm³ was manufactured at a cement/wood particle/water weight ratio of 2.5:1.0:1.25. Hand-formed mats of 230 x 230 mm were cold pressed to a targeted thickness of 12 mm and kept in an oven set at 60°C for 24 h. Afterwards, CBP was wrapped with a polyvinylchloride (PVC) film immediately, followed by curing for 28 days at room temperature (conventional). Four specimens of 50 x 210 mm prepared from these boards were then treated with (1) gaseous CO₂; and (2) supercritical CO₂. In order to estimate long term of CBP degradation, the following two types of experiment were conducted at various levels of CO₂ pressures and concentrations for various treatment times. In the first experiment, specimens were subjected in a reaction cell surrounded by a water jacket set at 26°C to CO₂ pressure of 1.0 MPa at gaseous phase for 30 min; 3, 5, 10, 24 h and 10 days treatment. The concentrations of CO₂ applied were 10, 50 and 100%. In the second experiment, specimens were subjected in a reaction cell surrounded by a water jacket set at 40°C to CO₂ pressure of 10 MPa at supercritical phase for 30 min; 3, 5, 10, 24 h and 10 days treatment. The concentrations of CO₂ applied were 10, 50 and 100%. Later, specimens of both experiments were dried in an oven drying at 80°C for 10 h, followed by conditioning at ambient temperature prior to property evaluation.

2.3 Evaluation of CBP properties
The mechanical and dimensional properties of the boards were tested in accordance with the Japan Industrial Standard (JIS) A 5908 (1994). The boards were cut into 50 x 210 mm samples for the static bending test and 50 x 50 mm samples for the internal bond (IB) strength, thickness swelling (TS), and water absorption (WA) tests. The static bending test was conducted using a three-point bending test over an effective span of 180 mm (15 times the board thickness) at a loading speed of 10 mm/min. Four test
samples were prepared from each treatment group for the foregoing tests, and the average values were calculated.

2.4 Measurement of residual values of CBP properties
The residual values of CBP properties (%) which indicates the degradation of CBP properties from the initial values (100%) was measured based on the degradation values of CBP properties treated at both the gaseous and supercritical CO2 in certain period compared to the optimum values (the initial values) of CBP properties treated in 30 min. The residual values of CBP properties were calculated from the following equation;

\[
\text{Residual values of properties } (%) = \left( \frac{P}{P_0} \right) \times 100
\]

where \( P \) is the values of CBP properties treated at both the gaseous and supercritical CO2 in certain period; and \( P_0 \) is the optimum values (the initial values) of CBP properties treated at both the gaseous and supercritical CO2 in 30 min.

2.5 Statistical Analysis
To estimate long term degradation of CBP affected by CO2 in gaseous and supercritical phase, the multiple regression analyses were performed with commercially available statistical software (SPSS Statistics 17.0, SPSS Japan Inc.) from the fallowing equation;

\[
y = ax_1 + bx_2 + c
\]

where \( y \) is the variable being predicted (CBP properties); \( x_1, x_2 \) are the predictor variables in the equations, where \( x_1 \) is the CO2 concentration (10, 50 and 100%) and \( x_2 \) is the treatment time (30 min, 3, 5, 10 and 24 h, 10 days); \( c \) is the \( y \)-intercept which indicates the point at which the regression plane intersects the \( y \)-axis when the values of predictor scores are all zero; \( a \) and \( b \) are the regression coefficients which are used as multipliers for the corresponding predictor variables (i.e., \( x_1 \) and \( x_2 \)).

3. Results and discussion

3.1 Effect of carbon dioxide phase, concentration and various treatment times on the properties of CBP
The average values for the mechanical properties (IB strength, MOR and MOE) and dimensional stabilities (TS and WA) of conventional cured CBP treated by CO2 in gaseous and supercritical phase at various concentrations and treatment times are presented in Table 1, which indicates that the IB strength, MOR, MOE, TS and WA were strongly affected by CO2 treatment in both the gaseous and supercritical CO2 conditions. With the increase in treatment time up to 30 min by the gaseous CO2 at 1.0 MPa of pressure or by the supercritical CO2 at 10 MPa of pressure; the mechanical properties (IB strength, MOR, MOE) and dimensional stabilities (TS and WA) were significantly improved with increasing the CO2 concentration compared to control values. However, in the short treatment time, the optimum properties of the supercritical CO2 cured CBP could achieve the higher values than those of the gaseous CO2. This condition indicated that the gaseous CO2 and the supercritical CO2 treatments improved the properties of CBP even after conventional curing process for 28 days. This finding shows different results compared to the results on previous research which indicated that the optimum properties of CBP manufactured by supercritical CO2 curing were almost similar to those of gaseous
### Table 1. Effect of carbon dioxide phase, concentration and various treatment times on the properties of CBP

| Properties | Unit | CO₂ concentration |
|------------|------|--------------------|
|            |      | 10%                |
|            |      | Control | 30 min | 3 h | 5 h | 10 h | 24 h | 10 days | 30 min | 3 h | 5 h | 10 h | 24 h | 10 days | 30 min | 3 h | 5 h | 10 h | 24 h | 10 days |
| IB         | MPa  | 0.59     | 0.67   | 0.66   | 0.65   | 0.64   | 0.62   | 0.59   | 0.79   | 0.77   | 0.75   | 0.74   | 0.73   | 0.71   | 0.59   | 0.86   | 0.84   | 0.83   | 0.81   | 0.79   | 0.77   | 0.75   | 0.74   | 0.73   | 0.71   | 0.59   | 0.86   | 0.84   | 0.83   | 0.81   | 0.79   |
| MOR        | MPa  | 10.09   | 10.26  | 10.25  | 10.23  | 10.21  | 10.20  | 10.09  | 10.96  | 10.89  | 10.82  | 10.72  | 10.68  | 10.42  | 10.09  | 12.2   | 12.01  | 11.97  | 11.65  | 11.50  | 11.13  |
| MOE        | GPa  | 3.49    | 3.61   | 3.54   | 3.53   | 3.48   | 3.43   | 3.42   | 3.49   | 4.18   | 4.04   | 4.01   | 3.97   | 3.90   | 3.83   | 3.49   | 4.82   | 4.72   | 4.67   | 4.46   | 4.35   | 4.15   |
| TS         | %    | 0.61    | 0.70   | 0.71   | 0.72   | 0.73   | 0.73   | 0.74   | 0.61   | 0.67   | 0.68   | 0.70   | 0.70   | 0.72   | 0.73   | 0.61   | 0.56   | 0.57   | 0.60   | 0.62   | 0.62   | 0.65   |
| WA         | %    | 21.39   | 20.20  | 20.34  | 20.20  | 20.31  | 20.37  | 21.56  | 21.39  | 19.42  | 19.52  | 19.63  | 19.81  | 20.21  | 20.32  | 21.39  | 20.05  | 20.07  | 20.13  | 20.37  | 21.56  | 22.07  |

STD is standard deviation
CO₂ curing, beside the addition of carbon dioxide at the gaseous of 0.5 MPa and 1.0 MPa yielded the lowest bonding properties and it showed improvement proportionally at a longer curing time [9]. In contrast, in our present study, it was evident that the optimum properties of CBP treated by supercritical CO₂ even after conventional curing process were higher than that by the gaseous CO₂, especially at 100% of CO₂ concentration. The additions of carbon dioxide at both the gaseous and supercritical CO₂-phase at 30 min improved the bending properties and dimensional stability of CBP even after conventional curing process for 28 days. Then, over the treatment from 3 h, these properties were continuously decreased. It should be noticed that the mechanical properties and dimensional stabilities of conventional cured CBP seemed to reach the higher values in the shorter treatment time with increasing of CO₂ concentration and pressure condition, however, the extension of treatment time over 3 h to 10 days resulted in any decreases of mechanical properties and dimensional stabilities of these boards, indicating that degradation process was accelerated in both gaseous and supercritical CO₂ treatments, as an effect of increasing the concentration and pressure conditions of carbon dioxide. The carbonation process in short period improved the mechanical and dimensional properties of CBP and in longer period degraded those properties.

Since the properties of CBP are improved by CO₂ treatment in both the gaseous and supercritical phase even after the conventional curing process, this phenomenon suggests cement will be cured at the initial period but degrade in longer period by the carbonation that occurs naturally over numerous years owing to the reaction with atmospheric CO₂ in ambient conditions.

Figure 1. Effect of CO₂ concentration and pressure conditions on the residual values of internal bond strength (IB) of cement-bonded particleboard (CBP) at various treatment times: 
\( a \) Pressure of 1.0 MPa (Gaseous phase), \( b \) Pressure of 10 MPa (Supercritical phase)

### 3.2 The residual values of CBP properties

The residual values of IB strength of conventional cured CBP exposed at different concentration and pressure of CO₂ at various treatment times are presented in Fig. 1, which indicates the linear relationships between the residual values of IB strength, and CO₂ concentration (%) and CO₂ pressure (MPa). As mentioned earlier, the residual values of CBP properties which indicate the degradation of CBP properties from the initial values (100%) was measured based on the degradation values of CBP properties treated at both the gaseous and supercritical CO₂ in certain period compared to the optimum values (the initial values) of CBP properties treated in 30 min. Although in our previous research, \( t^{\sqrt{7}} \) (min) was performed in treatment time, however, in this experiment the treatment time (min) was performed in natural logarithm or \( \ln(x) \) to obtain the best coefficient of determination \( R^2 \) between the properties of CBP and the affecting factors. Figure 1 shows the residual values of IB strength of CO₂-treated boards decreased proportionally when the CO₂ concentration and pressure applied were increased over a longer treatment time. At CO₂ pressure of 1.0 MPa or in gaseous phase, the residual values of IB strength were obtained 88% at 10 days treated by 100% of CO₂ concentration. In contrast, the residual values of IB strength were 93.2% when 10% of CO₂ concentration was applied in 10 days.
The residual values of IB strength were 90% when 50% of CO2 concentration and 1.0 MPa of CO2 pressure were applied in 10 days. These residual values of IB strength were almost similar to those obtained by conventional CBP treated by 50% of CO2 concentration at 10 MPa in 24 h. A similar trend was observed for conventional CBP treated at 10 MPa of CO2 pressure or in supercritical phase as shown in Fig. 1b. Addition of 10, 50 and 100% of CO2 concentration at 10 MPa of CO2 pressure over the treatment time from 3 h to 10 days resulted in degradation of the IB strength. The residual values of IB strength were 86.3% at CBP treated by 10% of CO2 concentration at 10 MPa of CO2 pressure in 10 days. However, the increasing of CO2 concentration to 100% over the treatment time from 3 h to 10 days showed in any decreases of the residual values of IB strength. The result shows the residual values of IB strength were decreased to about 76.6% at CBP treated by 100% of CO2 concentration at 10 MPa of CO2 pressure in 10 days.

**Figure 2.** Effect of CO2 concentration and pressure conditions on the residual values of modulus of rupture (MOR) of cement-bonded particleboard (CBP) at various treatment times: a Pressure of 1.0 MPa (Gaseous phase), b Pressure of 10 MPa (Supercritical phase)

**Table 2.** Multiple regression summary for variables of CO2 concentration and treatment time to CBP properties at different CO2 pressures

| Experiments       | Properties | Equation determined                      | $R^2$      | Corrected $R^2$ |
|-------------------|------------|------------------------------------------|------------|-----------------|
| 1.0 MPa (Gaseous CO2-phase) | IB        | IB = 0.0203 (CO2) - 1.64 ln (t) + 107    | 0.762      | 0.730           |
|                   | MOR       | MOR = 0.0042 (CO2) - 2.26 ln (t) + 108   | 0.708      | 0.690           |
|                   | MOE       | MOE = 0.0331 (CO2) - 1.57 ln (t) + 107   | 0.825      | 0.802           |
|                   | TS        | TS = 0.0458 (CO2) + 1.49 ln (t) + 92.2   | 0.805      | 0.779           |
|                   | WA        | WA = 0.0349 (CO2) + 0.974 ln (t) + 94.1  | 0.643      | 0.595           |
| 10 MPa (Supercritical CO2-phase) | IB        | IB = 0.0287 (CO2) - 2.87 ln (t) + 109    | 0.893      | 0.879           |
|                   | MOR       | MOR = 0.0288 (CO2) - 2.86 ln (t) + 109   | 0.891      | 0.877           |
|                   | MOE       | MOE = 0.0142 (CO2) - 3.19 ln (t) + 113   | 0.903      | 0.890           |
|                   | TS        | TS = 0.0320(CO2) + 2.60 ln (t) + 88.4    | 0.824      | 0.801           |
|                   | WA        | WA = 0.0381 (CO2) + 1.30 ln (t) + 92.4   | 0.713      | 0.675           |

*ln is natural logarithm, $R^2$ is coefficient of determination*

Similar relationship was found in the case of our previous study on the treatment by supercritical CO2 at the longer time span. When 10, 50 and 100% of CO2 concentration were applied at 1.0 MPa of
CO₂ pressure over the treatment time from 3 h to 10 days, the degradation of CBP still occurred although the longer treatment time resulted in a small decrease of the IB values. In contrast, when increasing the CO₂ pressure to 10 MPa at 100% of CO₂ concentration for 10 days, the residual values of IB strength were decreased drastically from 86.3% to about 76.6%. This finding shows that CO₂ in supercritical phase degraded the IB strength of CBP in rapid rate with longer treatment time compared to that in gaseous phase.

**Figure 3.** Effect of CO₂ concentration and pressure conditions on the residual values of modulus of elasticity (MOE) of cement-bonded particleboard (CBP) at various treatment times:

a Pressure of 1.0 MPa (Gaseous phase), b Pressure of 10 MPa (Supercritical phase)

Figures 2 and 3 show the effect of CO₂ concentration and pressure conditions on the residual values of MOR and MOE of conventional cured CBP at various treatment times. The results show the residual values of MOR and MOE were decreased significantly over the treatment time from 3 h to 10 days at 100% of CO₂ concentration with 10 MPa of CO₂. The residual values of MOR and MOE were 91.7% and 86.2%, respectively, in 10 days, when 100% of CO₂ concentration and 1.0 MPa of CO₂ pressure were applied (Fig. 2a, 3a). However, the increasing of CO₂ pressure to 10 MPa over the treatment time from 3 h to 10 days showed in any decreases of the residual values of MOR and MOE. It was observed that the residual values of MOR and MOE were decreased significantly over the treatment time from 3 h to 10 days at 100% of CO₂ concentration with 10 MPa of CO₂ pressure. The residual values of MOR and MOE of conventional cured CBP were decreased to about 77.6% and 78.7%, respectively, in 10 days (Fig. 2b, 3b). These results indicated that the degradation of the bending strength of CBP are mainly affected by CO₂ concentration, CO₂ pressure and treatment time.

**Figure 4.** Effect of CO₂ concentration and pressure conditions on the residual values of thickness swelling (TS) of cement-bonded particleboard (CBP) at various treatment times:

a Pressure of 1.0 MPa (Gaseous phase), b Pressure of 10 MPa (Supercritical phase)
As clarified in previous researches, [9,10] the presence of carbon dioxide is believed to increase the mechanical properties of CBP during a short treatment time, even after the conventional curing of 28 days, however, with a longer treatment time against CO2 in higher concentrations and pressures or in supercritical phase, it was considered that the mechanical properties of CBP degraded rapidly compared to the lower concentrations and pressures of CO2 or in gaseous phase. On the other hand, by exposing CBP to higher concentrations and pressures of CO2, beside increased the mechanical properties of conventional cured CBP in the short treatment time, the degradation process could be accelerated in the longer treatment time over 3 h. The degradation of IB strength of CBP may be due to the degradation on the core-layer of these boards, whereas, the degradation of MOR and MOE of CBP is due to the degradation on the surface-layer. The degradation process was identified due to the ease of penetration and diffusion of supercritical CO2 into the micro pores of the cement matrix caused by the low viscosity and high diffusivity of this media, providing enhanced reaction rate and continuous process of carbonation [16].

Figure 4 shows the effect of CO2 concentration and pressure conditions on the residual values of TS of conventional cured CBP at various treatment times. The residual values of TS of CBP increased with increasing the concentration and pressure conditions. The residual values of TS were 113.4% in 10 days, when 100% of CO2 concentration and 1.0 MPa of CO2 pressure were applied (Fig. 4a). The residual values of TS of CBP were increased to about 118.4% at 100% of CO2 concentration with 10 MPa of CO2 pressure in 10 days (Fig. 4b). These results show the same condition to WA of CBP, indicating the degradation of dimensional stabilities of conventional cured CBP increased by increasing of CO2 concentrations, CO2 pressures and treatment times. In general, the short treatment time of CO2 in supercritical phase improved the dimensional stability of conventional cured CBP. However, the dimensional stabilities were degraded when these boards treated at 100% of CO2 concentration at 10 MPa of CO2 pressure or in supercritical phase over a longer treatment time, suggesting that the supercritical CO2 treatment over a longer treatment time may result in degradation of dimensional stabilities of conventional cured CBP, which could result from the carbonation process.

3.3 The estimation of long term degradation of CBP affected by CO2 in gaseous and supercritical phase
To estimate long term degradation of CBP affected by CO2 in gaseous and supercritical phases, the following multiple regression model was applied:

\[ y = a \text{ (CO2 concentration)} + b \ln \text{ (time)} + c \]  

where \( y \) is the CBP properties (IB strength, MOR, MOE, TS and WS), \( a, b \) and \( c \) are constants, \( \ln \) is natural logarithm.

The constants \( a, b, \) and \( c \) and the coefficient of determination \( (R^2) \) are summarized in Table 2. For all factors affecting the degradation process, linear relationships were clearly observed. The coefficient of determination \( (R^2) \) for Eq.(3) between the IB strength of the samples, CO2 concentration and treatment time at 1.0 MPa and 10 MPa of CO2 pressure were 0.762 and 0.893, respectively, indicating that CO2 treatment in both gaseous phase (at 1.0 MPa of CO2 pressure) and supercritical CO2 phase (at 10 MPa of CO2 pressure) affect not only enhanced the mechanical properties of CBP in the short treatment time, but also degraded these properties in the longer treatment time. The \( R^2 \) values showed a good linearity \( (R^2 > 0.891) \) for the other properties such as MOR and MOE treated at 10 MPa of CO2 pressure. The \( R^2 \) values between the TS and WA of the samples, CO2 concentration, and treatment time at 1.0 MPa were 0.805 and 0.643, respectively; and at 10 MPa of CO2 pressure were 0.824 and 0.713, respectively. From these coefficient determination values, it is obvious that the CO2 concentration, CO2 pressure and treatment time affected the degradation of IB strength, MOR, MOE, TS and WA of CBP.

From the multiple regression equation (3), the long term degradation is estimated to obtain the half-value (50%) of initial values (100%) of CBP properties. In gaseous phase or using 1.0 MPa of CO2 pressure, the long term degradation of CBP to obtain half-value of the residual values on the IB strength...
The IB strength and MOR were $4.6 \times 10^9$ and $2.7 \times 10^5$ years, respectively. However, in supercritical phase or using 10 MPa of CO$_2$ pressure, the long term degradation of CBP to obtain the half-value of the residual values on the IB strength and MOR were $3.5 \times 10^3$ and $4.7 \times 10^3$ years, respectively. These results show the times required for degradation to obtain half-values of such properties treated at 10 MPa of CO$_2$ pressure or under supercritical phase was markedly short compared to the times at 1.0 MPa of CO$_2$ pressure or under gaseous phase. It seemed reasonable to conclude that some degradation occurred at CBP during treatment against CO$_2$ in higher concentrations and pressures or in supercritical phase over a longer treatment time, degrading the mechanical properties and dimensional stabilities of CBP in rapid rate compared to in lower concentrations and pressures of CO$_2$ or in gaseous phase. However, these validities of the above-estimations need further investigation concerning variability of the concentration and pressure of CO$_2$ for exact prediction of long term degradation of CBP, especially at ambient condition.

4. Conclusions

The properties of CBP are improved by CO$_2$ treatment in short period in both gaseous and supercritical phases even after the conventional curing process. These properties, however, over the longer treatment time degraded in rapid rate against CO$_2$ treatment in both gaseous and supercritical conditions. It was considered that the degradation of CBP increased with increasing the CO$_2$ concentration, CO$_2$ pressure and treatment time. With the longer treatment time against CO$_2$ in higher concentration and pressure or under supercritical phase, the residual values of mechanical properties of CBP were decreased; indicating CBP performance was degraded rapidly compared to treatment in the lower concentration and pressure of CO$_2$ or under gaseous phase. Although high coefficient determination values between the residual values of CBP properties, and the treatment time and CO$_2$ concentration were observed, and the simple linear model was found to estimate the long term degradation of CBP among the properties and affecting factors, these validities of the estimations need further investigation concerning variability of the concentration and pressure of CO$_2$ for exact prediction of long term degradation of CBP, especially at ambient condition.
References

[1] Al-Kadhimi T K H, Banfill P F G, Millard S G, Bungey J H 1996 Accelerated carbonation procedure for studies on concrete. Adv. Cem. Res. 47 pp 8

[2] Ngala V T, Page C L 1997 Effects of carbonation on pore structure and diffusional properties of hydrated cement paste Cem. Concr. Res. 27 (7) pp 995–1007

[3] Johannesson B, Utgenannt P 2001 Microstructural changes caused by carbonation of cement mortar Cem Concr Res 31 pp 925–931

[4] Arandigoyen M, Bicer-Simsir B, Alvarez Jl, Lange DA (2006) variation of microstructure with carbonation in lime and blended pastes. Appl Surf Sci 252 pp 7562–7571

[5] Garcia-Gonzales CA, Hidalgo A, Andrade C, Alonso MC, Fraile J, Lopez-Periago AM, Domingo C (2006) Modification of composition and microstructure of Portland cement pastes as a result of natural and supercritical carbonation procedures. Ind Eng Chem Res 45 pp 4985–4992

[6] Garcia-Gonzales CA, Hidalgo A, Fraile J, Lopez-Periago AM, Andrade C, Domingo C (2007) Porosity and water permeability study of supercritical carbonated cement pastes involving mineral additions. Ind Eng Chem Res 46 pp 2488–2496

[7] Bertos MF, Simons SJR, Hills CD, Carey PJ (2004) A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO2. J Hazard Mater 112 pp193–205

[8] Sisomphon K, Frank L (2007) Carbonation rates of concretes containing high volume of pozzolanic materials. Cement and Concrete Research 37 pp 1647–1653

[9] Hermawan D, Hata T, Umemura K, Kawai S, Nagadomi W, Kuroki Y (2001) Rapid production of high-strength cement-bonded particleboard using gaseous or supercritical carbon dioxide. J Wood Sci 47 pp 294–300

Acknowledgments
The authors thank the Directorate of Higher Education; Ministry of National Education-Indonesia for their finance support by DIKTI scholarship.