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Research Article

Using the Maturity Method in Predicting the Compressive Strength of Vinyl Ester Polymer Concrete at an Early Age

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The compressive strength of vinyl ester polymer concrete is predicted using the maturity method. The compressive strength rapidly increased until the curing age of 24 hrs and thereafter slowly increased until the curing age of 72 hrs. As the MMA content increased, the compressive strength decreased. Furthermore, as the curing temperature decreased, compressive strength decreased. For vinyl ester polymer concrete, datum temperature, ranging from −22.5 to −24.6°C, decreased as the MMA content increased. The maturity index equation for cement concrete cannot be applied to polymer concrete and the maturity of vinyl ester polymer concrete can only be estimated through control of the time interval Δt. Thus, this study introduced a suitable scaled-down factor (n) for the determination of polymer concrete's maturity, and a factor of 0.3 was the most suitable. Also, the DR-HILL compressive strength prediction model was determined as applicable to vinyl ester polymer concrete among the dose-response models. For the parameters of the prediction model, applying the parameters by combining all data obtained from the three different amounts of MMA content was deemed acceptable. The study results could be useful for the quality control of vinyl ester polymer concrete and nondestructive prediction of early age strength.

1. Introduction

Polymer concrete, wherein cement hydrate binder of cement concrete is completely replaced with a polymeric binder, is entirely different from cement concrete in terms of developed characteristics. Polymer concrete, with characteristics of rapid hardening, high strength, excellent adhesion, better water-tightness, freeze-thaw durability, and chemical resistance compared to cement concrete, is widely used in the construction industry [1]. Polymer concrete is employed chiefly as a patching material for repair work and overlays for bridge decks in cast-in-place applications, as well as in precast applications such as machine tool structures, building panels, utility boxes, and underground junction boxes [2].

As binders for polymer concrete, thermosetting resins such as unsaturated polyester, epoxy, acrylic, and vinyl ester are being used, and they show different physical and mechanical properties depending on the binder types [3–5]. This study used a vinyl ester resin, modified by adding an MMA monomer for the purpose of lowering viscosity and thus enhancing workability, as a binder. Vinyl ester resin has excellent chemical and corrosion resistance coupled with outstanding heat performance, thus making it a good choice for practical applications, such as swimming pools, sewer pipes, and solvent storage tanks [6, 7].

In terms of the quality control of polymer concrete, the most important aspect is to predict strength by a nondestructive test method so that the opening time for cast-in-place applications and the appropriate removal time for a mold in precast applications can, respectively, be decided. However, while strength development for cement concrete is caused by the hydration reaction of cement (binder), in polymer concrete it is caused by the polymerization of a polymer resin (binder). Polymer concrete's strength development consequently has the characteristic of being affected by temperature only and not humidity, whereas the strength development of cement concrete is affected by temperature and humidity.

The maturity method is based on the basic theory that since there is a certain relationship between the maturity index and concrete strength, identical maturity will lead to identical strength, even if curing temperature and curing time differ. In the literature on cement concrete's maturity, there are many studies on the prediction of early age strength [8–11], and there are also numerous studies on the prediction of late age strength using a modified maturity model [12, 13]. Research on the prediction of concrete's setting time through maturity methods has also been conducted [14, 15]. There are also studies applying maturity methods to the estimated compressive strength of mass concrete [16] and to the fracture parameters of site-casting dam concrete [17]. In addition, there is a study regarding evaluation of the maturity method to estimate concrete strength based on ASTM 1074 [18]. Despite the significant body of research on testing the maturity of cement concrete, it is difficult to find studies intended to be applied to polymer concrete except for a work by Ohama et al. [19].

As mentioned above, applying a maturity method to polymer concrete's early age strength prediction is sufficiently reasonable. But since polymer concrete has a fast reaction process, hardening time, and strength development speed, the maturity equation currently being applied to cement concrete has to be modified in order to be applicable. Therefore, the goal of this study is to derive a model suitable for the prediction of compressive strength at an early age, within 72 hours for vinyl ester resin polymer concrete with various MMA content, and identify suitable applications.

2. Background

The study of concrete's maturity involves estimating a maturity index and a maturity index-based prediction of strength. Below is a review of the literature published thus far.

2.1. Maturity Estimation Model. In the 1950s the need to estimate the effects of steam curing temperature on strength development led to the development of maturity methods that were aimed at accounting for the combined effects of time and temperature on the strength development of concrete [20].

These ideas led to the well-known Nurse-Saul maturity function [21].

$$M = \sum (T - T_o) \cdot \Delta t, \tag{1}$$

where M is the maturity index, T is the average concrete temperature during the time interval Δt, T_o is the datum temperature, t is the elapsed time, and Δt is the time interval.

The equivalent age maturity function, originally introduced by Rastrup [22], and shown in (2), is considered to be almost on par with (1) in terms of convenience.

$$t_e = \frac{\sum (T - T_o)}{(T_r - T_o)} \cdot \Delta t, \tag{2}$$

where t_e is the equivalent age at the reference temperature and T_r is the reference temperature.

Equation (3) is an equivalent age maturity function empirically developed by Hansen and Pedersen [23]. This function is based on the Arrhenius equation, used to describe temperature's effect on the rate of a chemical reaction.

$$t_e = \sum e^{(-E/R)[1/T - 1/T_r]} \Delta t, \tag{3}$$

where t_e is the equivalent age at the reference temperature, E is the apparent activation energy, R is the universal gas content, T is the average concrete temperature during the interval Δt, and T_r is the absolute reference temperature.

Carino et al. [21] proposed (4) which can calculate an equivalent age at the reference temperature. This is simpler than (3) but the calculated ages show similar values.

$$t_e = \sum e^{B(T - T_r)} \Delta t, \tag{4}$$

where B is the temperature sensitivity factor, T is the average concrete temperature during the time interval Δt, and T_r is the reference temperature.

These models were proposed for applications of cement concrete. As mentioned above, however, since there are differences in the hardening reaction process, hardening time, and strength development between polymer concrete and cement concrete, it is necessary to modify the maturity method used for cement concrete to be applicable to polymer concrete. In general, the polymer concrete has a very high strength at an early age and shows ultimate strength within a 24 h curing period. Accordingly, it is necessary to minimize the effect of Δt (time interval) on the maturity method for polymer concrete [19].

Reflecting the considerations noted above in (1) and modifying the same leads to

$$M = \sum (T - T_o) \cdot \Delta t^n, \tag{5}$$

where M is the maturity index, T is the average curing temperature, T_o is the datum temperature, t is the elapsed time, Δt is the time interval, and n is the scaled-down factor and is less than 1.

2.2. Strength Prediction Model. No less important than the maturity index is the strength prediction model, because regardless of how accurately the maturity index is estimated, the foregoing is meaningless if the strength prediction is inaccurate. A best-fit smooth curve is drawn through the data, or a regression analysis may be used to determine the best-fit curve for an appropriate strength-maturity relationship [21].

One of the popular strength-maturity relationships is the following logarithmic equation [21]. In 1956, Plowman

[24] suggested the following semilogarithmic function as an appropriate strength-maturity relationship.

$$S = a + b \log(M), \tag{6}$$

where S is the strength of the maturity index, M is the maturity index, and a and b are regression coefficients.

This equation is popular as it is simple, but it has a deficiency, too. Specifically, this equation plots a straight line and thus it can fairly accurately predict strength for intermediate maturity values but it has an obvious inadequacy for low or high values of the maturity index [8, 21].

In 1978, Lew and Reichard [25] proposed the following nonlinear regression formula by analyzing the relationship between the results of a compressive strength test and maturity.

$$S = \frac{K}{1 + Ka\left[\log(M - 30)\right]^{b}}, \tag{7}$$

where K, a, and b are numerical constants, M is the maturity of concrete, 30 is the maturity below which the strength is effectively 0, and S is the compressive strength of concrete.

The logistic curve [26] is used to express population growth as a mathematical model. It is an S-shaped curve with bilateral symmetry around the inflection point. The curve's inflection point is formed at the point at which S equals $Su/2$ ($S = Su/2$), and the curve has bilateral symmetry.

$$S = \frac{a}{1 + be^{-cM}}, \tag{8}$$

where S is the compressive strength, M is the maturity index, and a, b, and c are parameters.

The previously described equations are based on the assumption that the limiting strength is not affected by maturity or equivalent age. But many researchers have pointed out that the equations are limited in their applications. Most importantly, they do not reflect the effect of maturity on the limiting strength. The following equations were formed by modifications to address such limitations.

In 1971, Chin [27] suggested that the strength-maturity relationship could be represented by a hyperbola with the following equation:

$$S = \frac{M}{1/A + M/S_u}, \tag{9}$$

where S is the strength, M is the maturity, S_u is the limiting strength as maturity tends to infinity, and A is the initial slope of the strength-maturity curve.

In 1985, Hansen and Pedersen [28] proposed the following exponential equation to represent the strength development of concrete:

$$S = S_u e^{-[\tau/M]^{\alpha}}, \tag{10}$$

where S_u is the limiting strength, M is the maturity, τ is a time constant, and α is a shape parameter.

Equation (11) (a modification of Gompertz curve equation in order to predict concrete's compressive strength) is widely used. The curve has the characteristics of rapid rising, slowing down, and then approaching a horizontal state [19]. The curve's inflection point is formed at the point at which S equals Su/e ($S = Su/e$), and the curve does not have bilateral symmetry.

$$S = Su \cdot \exp\left(-a \cdot e^{-b} \cdot \log M\right), \tag{11}$$

where S is the compressive strength, Su is the limiting compressive strength, and a and b are parameters.

As shown above, many models have been proposed for strength prediction. The models were proposed before computer programming technology became commonly used. Currently, many computer programs related to prediction models are commercially available and optimum models can easily be obtained.

Table 1: Properties of vinyl ester resin.

Density (25°C)	Viscosity (20°C, mPa·s)	Vapor density	Styrene content (wt%)
1.2	250	3.6	45

Table 2: Properties of MMA monomer.

Density (25°C)	Viscosity (20°C, mPa·s)	Molecular weight (g/mol)	Appearance
0.9420	0.56	100	Transparent

Table 3: Properties of MEKPO.

Component	Specific gravity (25°C)	Active oxygen
MEKPO 55% DMP 45%	1.12	10.0

3. Materials

3.1. Vinyl Ester Resin. Vinyl ester (VE) resin is the combined product of an epoxy resin and an unsaturated carboxylic acid such as acrylic or methacrylic acid. The vinyl ester resin used in this study is a bisphenol-type epoxy vinyl ester resin and its properties are listed in Table 1.

3.2. MMA Monomer. Methyl methacrylate (MMA), a colorless and transparent liquid, is manufactured by oxidizing isobutylene, extracted from C4 raffinate, in a gaseous state, thus making methacrylic acid. It is then esterified with methanol. Its properties are provided in Table 2.

3.3. Initiator. A DMP solution with 55% methyl ethyl ketone peroxide (MEKPO) is used as an initiator to harden the vinyl ester resin. The initiator's properties are listed in Table 3.

3.4. Promotor. Vinyl ester resin and MMA do not harden when only an initiator is added in the copolymerization state,

Table 4: Properties of cobalt naphthenate.

Density (25°C)	Boiling point (°C)	Appearance
0.95	110.6	Violet liquid

and hence a promotor is necessary to promote a reaction. This study used cobalt naphthenate as a promotor, and its properties are listed in Table 4.

3.5. Aggregate. Aggregate, if high in moisture content, weakens adhesion between the binder and aggregate surface and thus lowers strength, and therefore it was dried so that the moisture content was kept at 0.5% or lower. Properties of the aggregate used are shown in Table 5.

3.6. Filler. Since the binder of polymer concrete is in the form of a liquid, a filler is needed. The filler fills in pores in the aggregates contributing to an improvement in durability and strength. This study used heavy calcium carbonate, and its properties and chemical components are provided in Tables 6 and 7.

4. Methods

4.1. Deciding Appropriate Mix Proportion. The mix proportion of polymer concrete varies depending on the type of polymeric binder, as well as the shape and grade of the aggregate. To obtain a desirable mix proportion, the amount of aggregate and filler is maximized and the amount of polymeric binder is minimized to the extent that a designated workability and strength can be obtained. The mix proportion of polymer concrete, obtained through several trial and error experiments, is shown in Table 8.

4.2. Compressive Strength Test. A compressive strength test was conducted, pursuant to ASTM C 579 (Standard Test Methods for Compressive Strength of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes). The specimen used was a Ø5 × 10 cm cylinder, and a 20-ton UTM (Instron 8502) was used for loading.

5. Results and Discussion

5.1. Compressive Strength. Test results of the compressive strength of vinyl ester polymer concrete at different MMA content, curing temperature, and curing age are shown in Table 9 and Figure 1. Also, the experimental data for this study were 48. In the test data, the compressive strength rapidly increased until the age of 24 hrs but thereafter slowly increased until the age of 72 hrs. This trend or tendency showed differences according to the MMA content and the curing temperature.

Regarding the effect of MMA content (0, 2.5, 5 wt%), an increase in MMA content led to a decrease in compressive strength. Hyun and Yeon [4] stated that, in UP-MMA polymer concrete, an increase in the ratio of MMA to UP led to a decrease in the compressive strength, and Patel et al. [29] reported that an increase in the styrene monomer content of vinyl ester resin led to a larger decrease in strength. The results of this study are thus similar to those of the previously mentioned studies.

Regarding temperature changes during hardening, the temperature of polymer concrete itself increased but curing temperature is used in the laboratory maturity test since temperature history of the field concrete is employed in estimating concrete strength. Looking at the effects of curing temperature (20, 10, 0, and −10°C), a decrease in curing temperature led to a marked decrease in compressive strength. The degree of the decrease in compressive strength according to the decrease in curing temperature was largest at a curing age of 3 hrs and gradually decreased with the elapse of time. This compressive strength can be considered lower than those of previous studies using other types of binders [3, 4, 30].

5.2. Scaled-Down Factor (n). In (5) (a modification of (1) to better estimate the maturity index of polymer concrete), the n value is a very important element. In this study, "n" will be called the scaled-down factor. While the value of n is 1 in the estimation of cement concrete's maturity index, it has to be less than 1 in the case of polymer concrete. The reason is that polymer concrete shows more rapid hardening than cement concrete. The reference design strength hence is a 28-day strength for cement concrete but a 7-day strength for polymer concrete.

Ohama et al. [19], to decide the value of n, substituted n = 1, 1/2, 1/3, and 1/4 into (5) to estimate the maturity index. And they analyzed the correlations with the compressive strength predicted by substituting the foregoing into the Gompertz curve equation. As a result, since the coefficient of correlation was highest at $n = 1/2$, it was adopted as the n value.

However, in this study, to find more accurate values, n values from 0.1 to 1.0 with intervals of 0.1 were substituted in (5). The maturity index was thus estimated and the compressive strength values obtained by actual tests were used as data for the commercially available modeling program (dose-response models), in order to analyze the correlations.

The relationship, obtained through a correlation analysis, between the coefficient of determination and the scaled-down factor (n value) is shown in Figure 2. Since the coefficient of determination (R^2), despite small differences therein, was largest at $n = 0.3$, this study applied that value to estimate the maturity index. The reason why this value is smaller than that suggested by Ohama et al. [19] ($n = 1/2$) is that the vinyl ester polymer concrete used in this study had a much higher compressive strength than the unsaturated polyester polymer concrete they studied, under subzero curing temperature and at early curing age.

5.3. Datum Temperature. In the calculation of the maturity of polymer concrete, datum temperature means a limited temperature below which concrete's strength does not increase. To accurately estimate the maturity index, it is, above all, important to determine the accurate datum temperature. Also, the compressive strength test data correctly measured according to curing temperature and curing age is necessary. This study used compressive strength values of curing age up to 72 hrs, because compressive strength markedly developed

Table 5: Physical properties of aggregate.

Size (mm)	Apparent density	Bulk density	Unit weight (kg/m^3)	Fineness modulus	Moisture content (%)	Organic impurities
0.08~8	2.64	2.62	1,648	3.09	<0.1	Nil

Table 6: Properties of heavy calcium carbonate.

Specific gravity	Bulk density (g/cc)	Moisture content (%)	pH	Mean grain size (μm)	Retained percentage of 325-mesh sieve
2.70	0.75	≦0.3	8.8	13	14.3

Table 7: Chemical components of heavy calcium carbonate (by percentage).

CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO	Ignition loss
53.7	0.25	0.09	2.23	0.66	42.4

Table 8: Mix proportion of polymer concrete.

Binder content (wt%)	Binder formulation			Filler (wt%)	Fine aggregate (wt%)
	VE : MMA (wt%)	MEKPO (phr*)	Cobalt naphthenate (phr*)		
12.0	100 : 0	2	2	18.00	70.00
11.5	97.5 : 2.5			17.25	71.25
11.0	95.0 : 5.0			16.50	72.50

*Parts per hundred parts of resin.

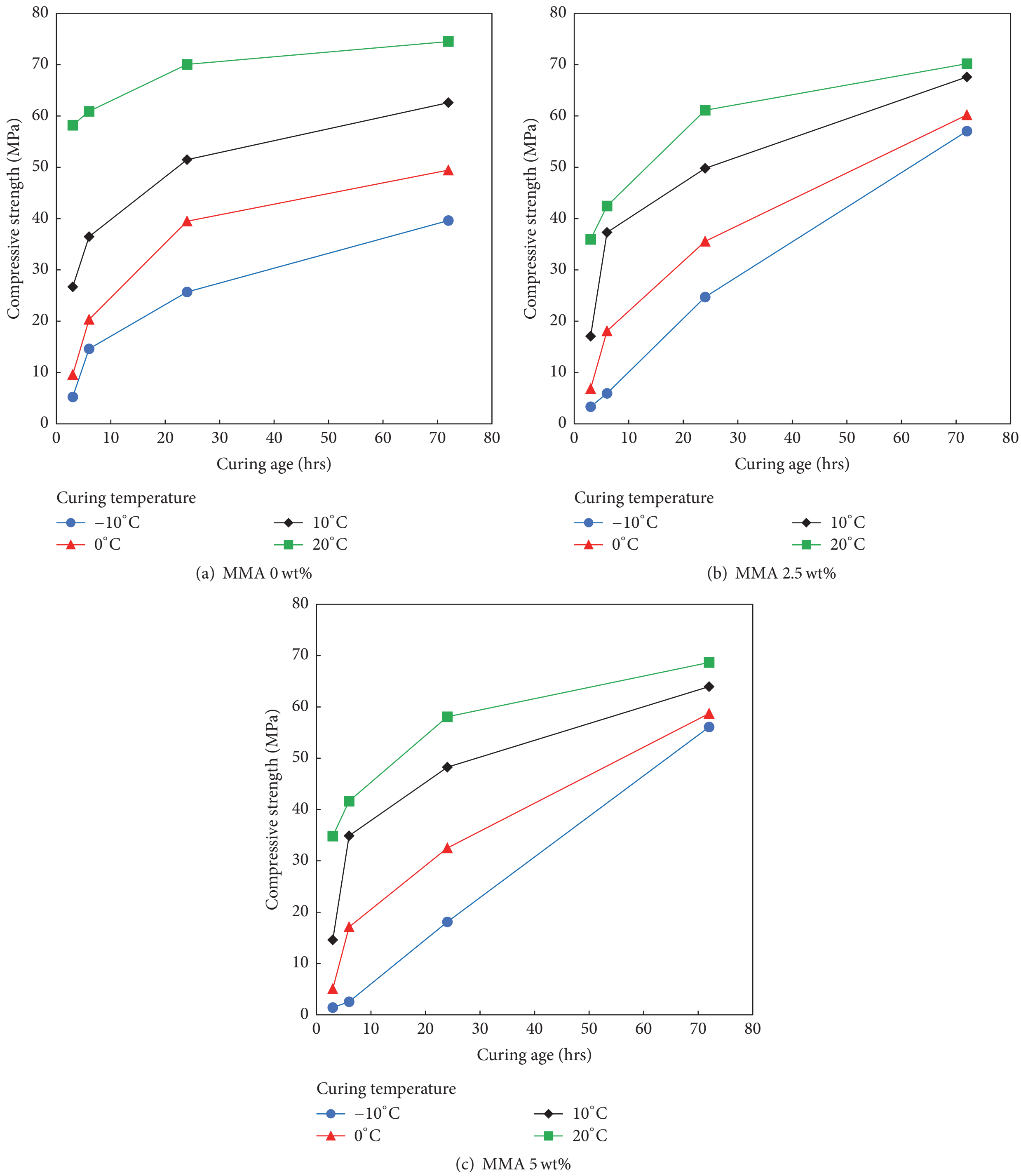
Table 9: Test results of compressive strength (by MPa).

MMA content (wt%)	Curing temperature (°C)	Curing age (hrs)			
		3	6	24	72
0	−10	5.25	14.62	25.71	39.62
	0	9.58	20.35	39.48	49.45
	10	26.70	36.49	51.48	62.59
	20	58.19	60.91	70.06	74.50
2.5	−10	3.34	6.84	17.08	35.95
	0	5.95	18.11	37.31	42.46
	10	24.73	35.58	49.79	61.12
	20	57.05	60.21	67.61	70.19
5.0	−10	1.41	5.05	14.58	34.82
	0	2.56	17.1	34.88	41.65
	10	18.11	32.51	48.24	58.08
	20	56.08	58.71	63.96	68.66

at this curing age and thereafter tended to increase very slowly.

Generally, the datum temperature applied to the maturity equations of cement concrete is −10°C [21], but −12°C is also used [8]. Datum temperature can sometimes fall from −10 to −15°C when an antifreezing admixture is used [19]. Polymer concrete, hardened by a polymerization reaction, shows high strength at an early curing age. The rate of strength development can also be controlled by the contents of the initiator and promotor for polymer resin binders. Polymer concrete does not need water for the hardening reaction, making it possible to predict that polymer concrete may have a lower datum temperature than does cement concrete with an antifreezing mixture added.

In Table 9, at a temperature of −10°C, there is a strong strength development even at a curing age of 3 hrs, and in this light it is seen that −10°C (cement concrete's datum temperature) cannot be used as the datum temperature for



(a) MMA 0 wt%

(b) MMA 2.5 wt%

(c) MMA 5 wt%

FIGURE 1: Curing age versus compressive strength with curing temperature.

polymer concrete. This can be understood from the fact that, as seen in Table 12, the maturity index is not 0 when the curing temperature is −10°C.

The following is a detailed explanation of the process to estimate the datum temperature. First, Figure 3, with age ($t^{0.3}$) as the x-axis and compressive strength as the y-axis, is prepared according to the MMA content and curing temperature. The primary regression equation can be obtained according to curing temperature by the least squares method, with the results shown in Table 10, where the regression coefficient "a" obtained according to curing temperature (hereinafter the "slope coefficient of strength") represents the trend or tendency of strength increase. Figure 4 is a diagram with curing temperature as the x-axis and the

Table 10: Computation results of the slope coefficient of strength ($n = 0.3$).

MMA content (wt%)	Curing temperature (°C)	$f_c = a(t^{0.3}) + b$ Constant		R^2
		a	b	
0	−10	14.756	−13.024	0.9829
	0	17.696	−11.447	0.9501
	10	15.717	7.757	0.9683
	20	7.555	48.341	0.9644
2.5	−10	14.603	−18.165	0.9313
	0	16.089	−11.467	0.9630
	10	15.739	6.196	0.8899
	20	5.976	49.860	0.9837
5.0	−10	14.868	−20.619	0.9754
	0	16.798	−15.025	0.8933
	10	17.009	−0.328	0.9252
	20	5.602	48.822	0.9907

Table 11: Calculation results of datum temperature.

MMA content (wt%)	Slope coefficient of strength				$y = ax^2 + bx + c$ (for Figure 4)				Datum temperature (T_o, °C)
	−10	0	10	20	a	b	c	$-R^2$	
0	14.756	17.696	15.719	7.555	−0.0278	0.0418	17.887	0.9986	−24.625
2.5	14.603	16.089	15.739	5.977	−0.0281	0.0189	17.225	0.9583	−24.425
5.0	14.868	16.798	17.009	5.602	−0.0333	0.0576	18.283	0.9440	−22.583

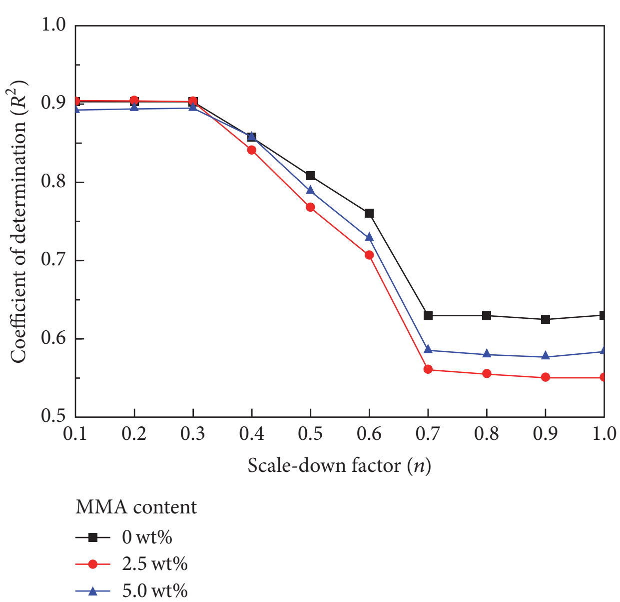


Figure 2: Scaled-down factor (n) versus coefficient of determination (R^2).

slope coefficient of strength as the y-axis. One only needs to find the temperature at which the slope coefficient of strength "a" is 0, by considering Figure 4 as the secondary curve. The secondary curve has two points at which "a" equals 0 ($a = 0$), wherein the high-temperature point represents the temperature at which the entire strength development ends and the low-temperature point represents the temperature at which the strength development is suspended by low temperature. Ultimately, the low-temperature point is the datum temperature used to calculate maturity. The estimation of the datum temperature based on this method is shown in Table 11.

Table 11 shows that a datum temperature, ranging from −22.5 to −24.6°C, despite the fact that there is not a large difference therein, decreased as the MMA content increased. With 3 hr and 72 hr compressive strengths at a curing temperature of −10°C being 5.25 MPa and 39.62 MPa, respectively, the datum temperature estimated in this study appears to be a realistic value.

5.4. Maturity Index. Common among (1) (the well-known and widely used Nurse-Saul maturity function), (2), (3), and (4) is the characteristic that the time interval Δt is not modified but is multiplied as it is. Note that these equations were proposed for use in applications for cement concrete.

However, polymer concrete, as mentioned above, has a completely different hardening mechanism. Cement concrete is hardened by the hydration of cement paste whereas polymer concrete is hardened by the polymerization of the polymeric resin. Since polymer concrete's hardening does not require moisture, air dry curing is used. In curing, cement concrete is affected by both temperature and moisture, but polymer concrete is affected by temperature alone. Strength prediction through the maturity method thus may be more suitable for polymer concrete than for cement concrete.

Table 12: Estimation results of the maturity index.

MMA content (wt%)	Curing temp. (°C)	Maturity index (°C · $t^{0.3}$) Curing age (hrs)			
		3	6	24	72
0	−10	20.33	25.03	37.95	52.76
	0	34.24	42.15	63.89	88.83
	10	48.14	59.27	89.84	124.91
	20	62.05	76.39	115.78	160.98
2.5	−10	20.06	24.69	37.43	52.04
	0	33.96	41.81	63.37	88.11
	10	47.86	58.93	89.32	124.19
	20	61.77	76.05	115.26	160.26
5.0	−10	17.49	21.54	32.65	45.39
	0	31.40	38.66	58.59	81.47
	10	45.30	55.77	84.54	117.54
	20	59.21	72.89	110.48	153.61

Polymer concrete, despite variations according to the amount of hardening agent or promotor that is added and the curing temperature, generally develops most of its strength at around a curing age of 24 hrs, at room temperature. So, (1), (2), (3), and (4), which were proposed to be applicable to cement concrete, cannot be applied to polymer concrete. According to a practical review of correlations between the maturity index estimated by substituting the elements of polymer concrete into these equations and the compressive strength of polymer concrete obtained in the test, the coefficient of determination (R^2) around 0.5 was found to be inapplicable.

Since the ultimate cause of this lies in the differences in curing speed, application is impossible without control of the time interval Δt. That is, since polymer concrete has a shorter curing time than cement concrete, the effect of Δt has to be reduced. Reflecting this, a modification can be made in (1). The maturity index estimated by substituting Table 11 datum temperature into (1) is shown in Table 12. According to the result, an increase in MMA content led to a decrease in the maturity index, but the difference was not large. The maturity index thus estimated could be useful in predicting the early age compressive strength of polymer concrete.

5.5. Prediction of Strength. Prediction models for strength, as shown in (6) through (11), are presented in various forms. Among them, (6), called a logarithmic equation, was suggested by Plowman and represents one of the popular strength-maturity relationships [21, 24]. This equation can predict the strength for intermediate maturity values fairly accurately but has a deficiency of noncoincidence for low or high values for the maturity index [8, 21].

Ohama et al. [19] used (11) (a modification of the Gompertz curve equation) to predict the compressive strength of polyester polymer concrete and claimed that there is a significant correlation. This was also the first study that used the maturity method to predict the strength of polymer concrete.

In this study, among the linear prediction-related, commercially available computer programs, a commercially available statistical analysis software package called Curve Expert Professional [31] was used.

Among the models mentioned here, the DR-HILL model (see (12)) had the best fit with the maturity index-compressive strength relationship among dose-response models.

$$S = \alpha + \frac{\theta M^{\eta}}{\kappa^{\eta} + M^{\eta}}, \tag{12}$$

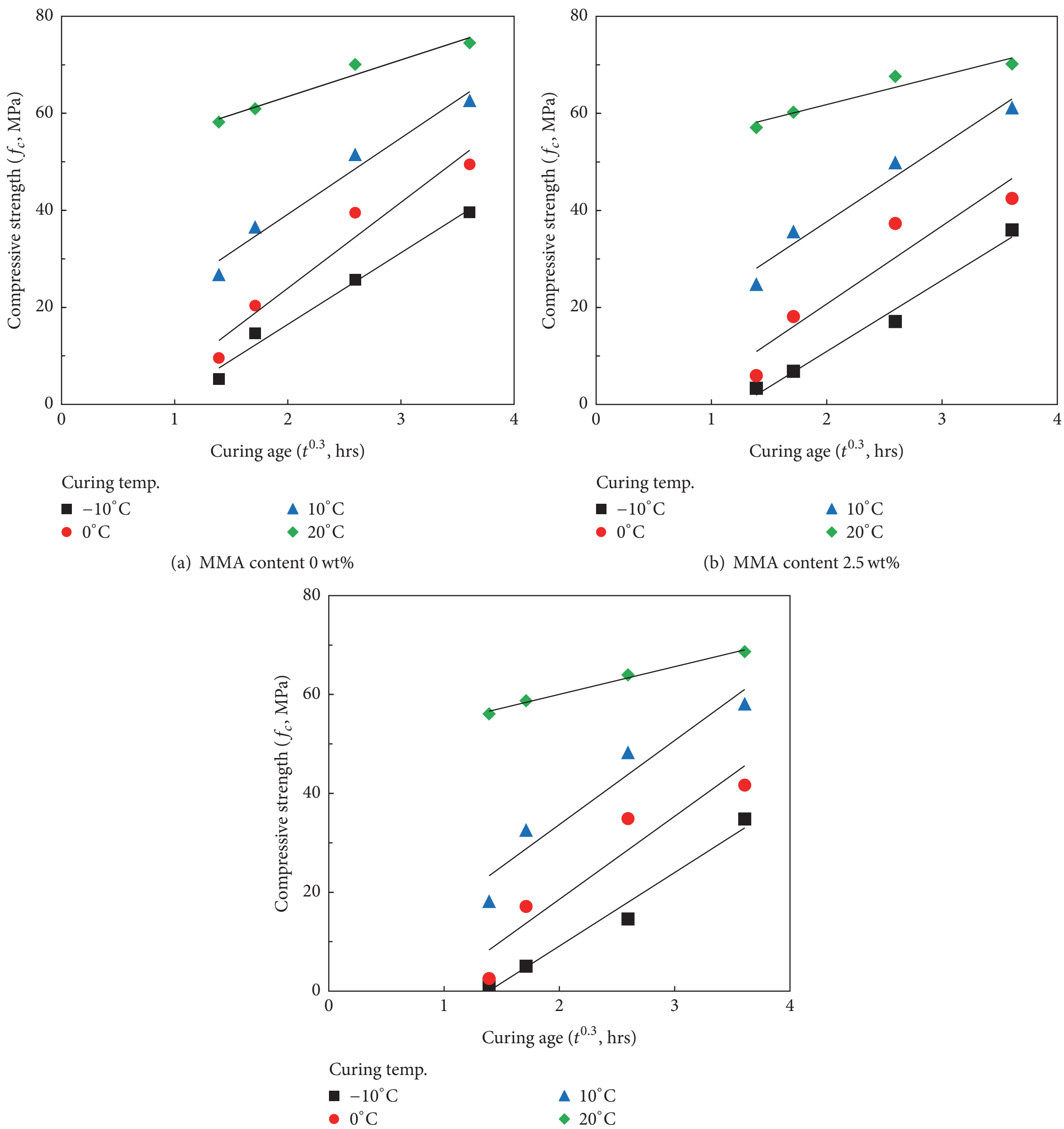
where S is the compressive strength (MPa), M is the maturity index (°C·hrs or °C·days), and α, θ, η, and κ are parameters.

The results of the regression analysis using this model are shown in Figure 5. And the parameters derived through the regression analysis are listed in Table 13, which is summarized according to MMA content, and the bottom line was obtained by combining the experimental data obtained according to the three different amounts of MMA content. To actually predict the compressive strength of vinyl ester polymer concrete, the parameter in the last part could be used for a regression analysis of the entire data.

6. Conclusions

This study predicted the early age compressive strength of vinyl ester polymer concrete using the maturity method, and the results are as follows.

(i) Regarding changes in compressive strength, the strength rapidly increased until the curing age of 24 hrs but thereafter slowly increased until the curing age of 72 hrs. As the MMA content increased, phase separation had a greater effect, thus lowering the compressive strength. As the curing temperature decreased, the compressive strength markedly decreased but the degree of the latter's decrease was reduced with the elapse of time.



(a) MMA content 0 wt%

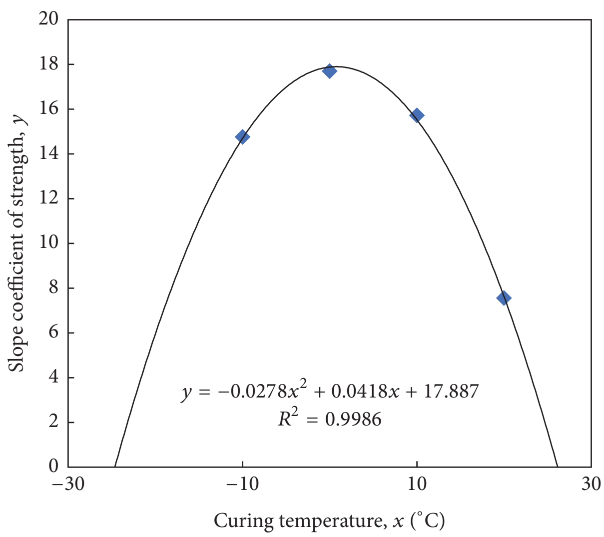
(b) MMA content 2.5 wt%

(c) MMA content 5.0 wt%

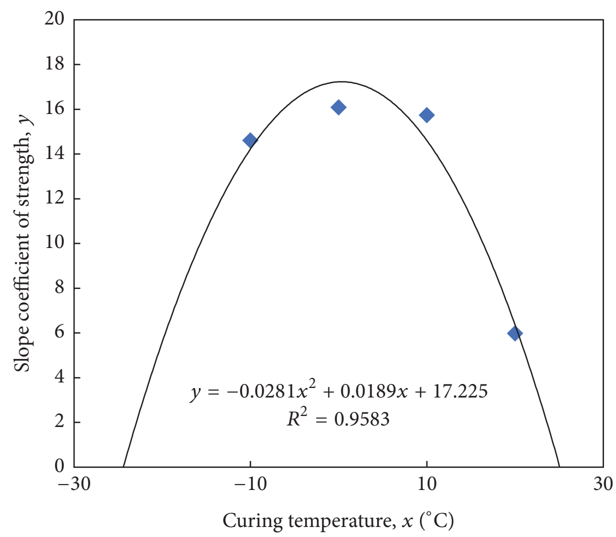
Figure 3: Curing age versus compressive strength for computation of the slope coefficient of strength.

Table 13: Parameters derived from (12).

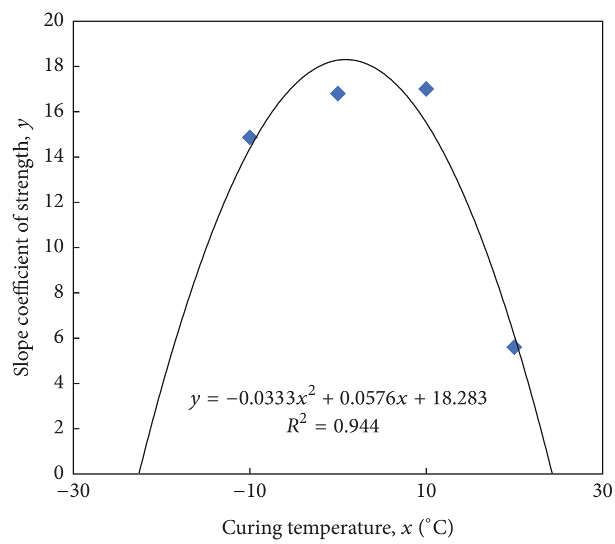
MMA content (wt%)	α	θ	η	κ	R^2
0	1.746991	72.896267	2.666858	56.080615	0.9029
2.5	−0.529111	67.473992	3.339196	53.013517	0.9039
5.0	−1.351659	66.593701	3.271513	50.539312	0.8947
Combination	−0.463439	69.670477	3.010200	53.060200	0.8965



(a) MMA content 0 wt%



(b) MMA content 2.5 wt%



(c) MMA content 5.0 wt%

FIGURE 4: Curing temperature versus the slope coefficient of strength for computation of datum temperature.

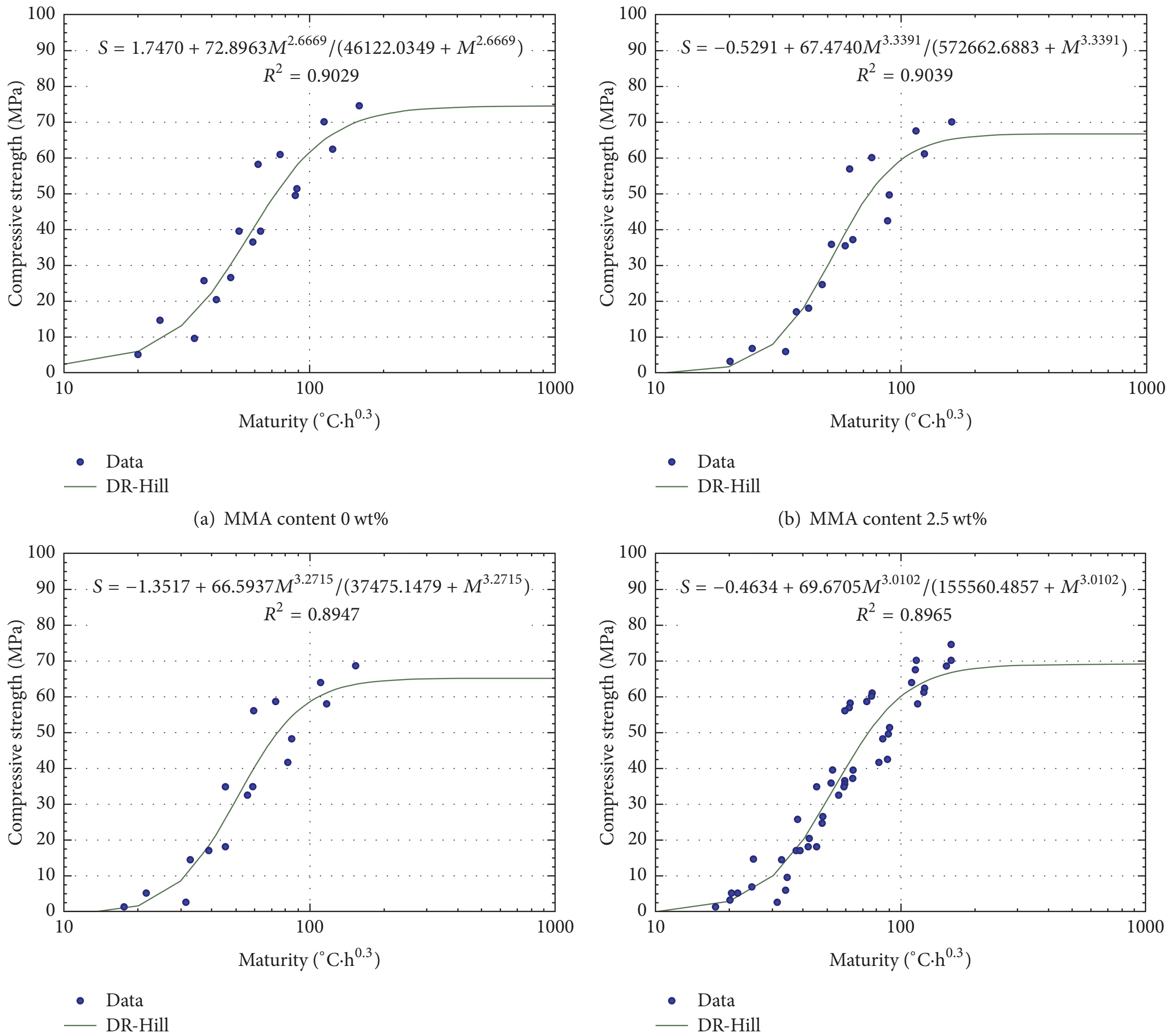
(ii) In (5), a function modified to suit the estimation of polymer concrete's maturity index, a scaled-down factor (n) is adopted. The value of "n" has to be lower than 1, and in the case of vinyl ester polymer concrete, 0.3 is the most suitable.

(iii) The datum temperature currently being applied to cement concrete, −10°C, was found to be inappropriate for vinyl ester polymer concrete. The datum temperature calculated in this study, ranging from −22.5 to −24.6°C, decreased as the MMA content increased, although the difference in temperature was not large.

(iv) Regarding the maturity index, various equations used for existing cement concrete were inapplicable to polymer concrete. The effect of the time interval Δt had to be reduced because it was found that the fundamental cause was the difference in curing speed.

(v) A software package called Curve Expert Professional was used to derive an appropriate compressive strength prediction model, and it was found that, among dose-response models, the appropriate model applicable to vinyl ester polymer concrete was DR-HILL, which is expressed as (12).

(vi) Although the parameters in (12) were calculated by regression analysis according to MMA content, in actual applications it may be acceptable to use the parameters calculated by combining all of the experimental data obtained according to the three different amounts of MMA content.



(a) MMA content 0 wt%

(b) MMA content 2.5 wt%

(c) MMA content 5.0 wt%

(d) Combination

FIGURE 5: Compressive strength- maturity curves.

(vii) The results of this study could be useful for quality control and nondestructive prediction of early age strength for vinyl ester polymer concrete, and, in the future, studies on late age strength should be conducted also.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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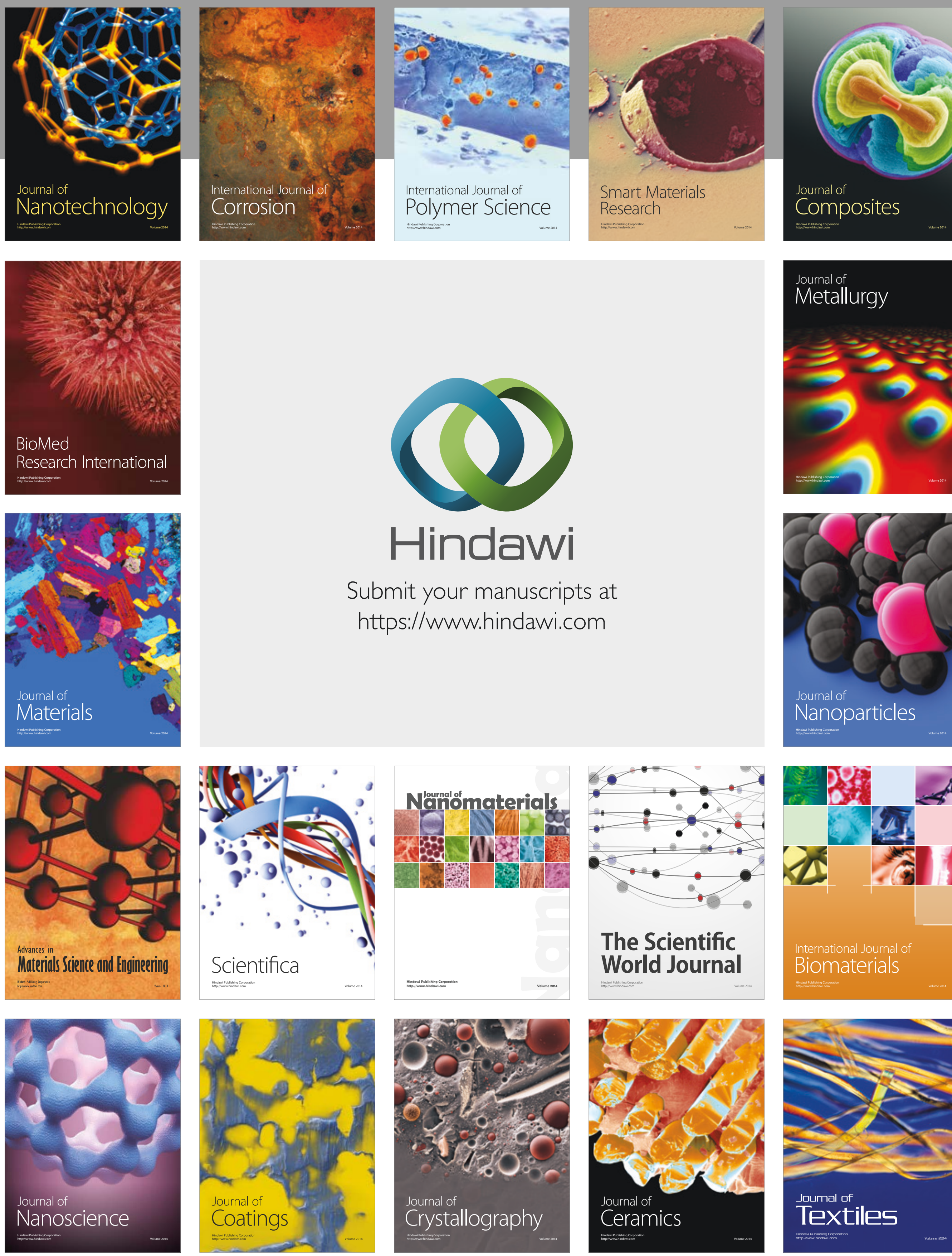
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