Hindawi
Advances in Materials Science and Engineering
Volume 2017, Article ID 3627251, 7 pages
https://doi.org/10.1155/2017/3627251

Research Article

Time-Dependent Behavior of Shrinkage Strain for Early Age Concrete Affected by Temperature Variation

Yu Qin,[1,2] Zhijian Yi,[1] Weina Wang,[1] and Di Wang[3]

[1] *School of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China*
[2] *CREEC (Chongqing) Survey, Design and Research Co. Ltd, Chongqing 400023, China*
[3] *Pavement Engineering Center, Technical University of Braunschweig, 38106 Braunschweig, Germany*

Correspondence should be addressed to Weina Wang; wwn0816@yeah.net

Received 12 August 2016; Revised 12 January 2017; Accepted 1 February 2017; Published 29 March 2017

Academic Editor: Charles C. Sorrell

Shrinkage has been proven to be an important property of early age concrete. The shrinkage strain leads to inherent engineering problems, such as cracking and loss of prestress. Atmospheric temperature is an important factor in shrinkage strain. However, current research does not provide much attention to the effect of atmospheric temperature on shrinkage of early age concrete. In this paper, a laboratory study was undertaken to present the time-dependent shrinkage of early age concrete under temperature variation. A newly developed Material Deformation Tester (MDT), which can simulate consecutive variation of atmospheric temperature, was used to collect the shrinkage strain of specimens and temperature data. A numerical model was established to describe the thermoelastic strain of a specimen. The results show that (1) there are several sharp shrinkages up to 600 μ for early age concrete in the first 3 days; (2) the absolute value of shrinkage strain is larger than thermal strain; and (3) the difference of shrinkage strain under temperature variation or constant temperature is up to 500 μ.

1. Introduction

The cracking of early age concrete is a major distress that affects structural integrity and sustainability. When concrete is restrained by itself or outside constraint, the strain generated by autogenous shrinkage and drying shrinkage can result in residual stress. When sufficient residual stresses develop (above approximately 50% of the strength), microcracking and damage start to occur in the interior of concrete. Microcracks are the precursor of further deterioration and may lead to lower long-term durability, shorter life span, and higher life cycle costs from maintenance operations.

The characteristics of shrinkage of early age concrete have been highlighted in a number of investigations [1–4]. Hobbs [5] investigated the effect of specimen geometry and curing period on the shrinkage of plain concrete specimens dried at 65% RH and 20°C. Terrill et al. [6] produced shrinkage curves for small concrete cylinders with varied curing times. Lura et al. [7] presented the results of an experimental study on the influence of curing temperature and type of cement on the autogenous deformations in early age concrete. Wong et al. [8] investigated experimentally the physical properties of reactive powder concrete at early age using fibre bragg gratings. Kim and Goulias [9] assessed the shrinkage behavior of concrete mixtures produced with aggregate from returned concrete. Aitcin et al. [10] presented that autogenous shrinkage occurs mainly during the initial setting to 1 d age and the rate of increase tends to decrease after 1 d.

The factors affecting shrinkage have already been widely discussed [11–13]. Bazant and Wu [14] formulated the constitutive law for shrinkage of concrete at variable humidity in a rate-type form. Brooks [15] assessed the influence of plasticizing and superplasticizing admixtures on long-term drying shrinkage of concrete. Bakharev et al. [16] investigated the effect of curing temperature on microstructure, shrinkage, and compressive strength of alkali-activated slag concrete. Nassif et al. [17] stated that fly ash and light weight aggregate improved the autogenous shrinkage performance. Jiang et al. [3] investigated experimentally autogenous shrinkage behaviors of high performance concrete containing fly ash and blast-furnace slag exposed to different isothermal

Table 1: Concrete mixture proportions.

Specimen group	w/c	Component kg/m^3					Sand ratio
		Cement	Water	FA	CA	Superplasticizer	
Group A	0.36	403	145	685	1167	6.05	0.37
Group B	0.44	330	145	712	1213	4.95	0.37

Note: w/c, water-cement ratio; FA, fine aggregate; CA, coarse aggregate.

Figure 1: Material Deformation Tester.

temperatures. Oliveira et al. [18] indicated that all the compositions (with or without shrinkage reducing admixtures and expansive product) have a higher long-term total shrinkage when subject to cure.

Most of the previous research dealing with shrinkage of early age concrete was carried out at constant temperature. However, for real concrete structures, ambient temperature has been in a state of change. The behavior of shrinkage is significantly affected by temperature variation.

In this study, several specimens were tested under air temperature variation in MDT. A numerical modeling approach was utilized to study the thermoelastic strain of the specimen. Shrinkage behavior of early age concrete is discussed based on the strain and temperature data.

2. Experimental Program

Two different mixes of concrete were studied and six prismatic specimens were used for each mix. The shrinkage strain of samples was measured at 2 min intervals in the first two days by MDT. The weights of specimens were determined at the start of test, and the end of the first 24 and 48 hours to count water loss. The relationship between shrinkage strain and air temperature variation was studied.

2.1. Materials. Ordinary Portland cement (OPC), equivalent to ASTM Type I, was used in the present study. Crushed limestone with a maximum size of 25 mm was chosen as coarse aggregate. River sand having a fineness modulus of 2.84 and a maximum size of 5 mm was used as fine aggregate. A polynaphthalene sulphonate superplasticizer was also used in mixes.

2.2. Mix Proportions. The mix proportions of concrete were designed in accordance with the absolute volume method. Two mixes commonly used for bridges in China are presented in Table 1. The dosage of superplasticizer is the 1.5% of cement weight.

2.3. Test Apparatus. Figure 1 illustrates the Material Deformation Tester (MDT) that was used in this study. The pictures showing the arrangement of the MDT are presented in Figure 2. The components of MDT consist of (1) test chamber, (2) casing, (3) temperature sensor, (4) deformation transfer rod, (5) bakelite pad, (6) fixing device, (7) casing, (8) displacement sensor, (9) insulating layer, (10) condenser tube, (11) glass plate, (12) specimen holder, (13) base, (14) compressor pipe, (15) printer, (16) industrial control computer, (17) A/D converter, (18) compressor, (19) cushioning, (20) beam, (21) load cell, (22) heating pipe, (23) specimens, and (24) fan.

There are six displacement sensors fixed on the top of test chamber. The displacement sensors and A/D converter are connected by wire. The measurement resolution of the sensor is three per ten thousandths and the accuracy is 0.1 micron. The sensors are used to convert the captured displacement signals into electrical signals exported to the A/D converter. The electrical signals are then transformed into digital signals and transmitted to an industrial control computer. Six load cells connected to A/D converter were installed in the base of test chamber.

2.4. Test Methods. The purpose of this test is to investigate the shrinkage strain of early age concrete affected by air temperature variation in July, in Northern China. Northern China represents the vast region just north of the Huai River-Qin Mountains line, at 33~53 degrees north latitude. The Huai River-Qin Mountains line is generally regarded as the geographical dividing line between Northern and Southern China. Summer is the best season for construction in Northern China. Therefore, July was selected as the time point of this laboratory test.

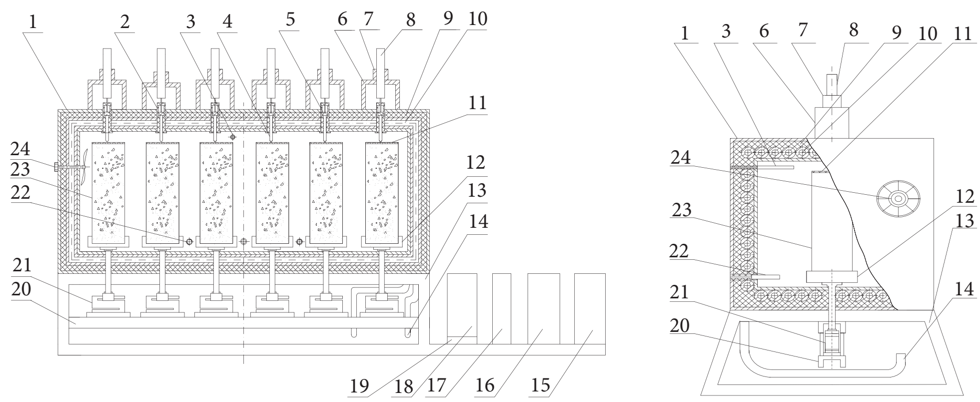


Figure 2: Components of the Material Deformation Tester.

The components of the mix were mixed. Specimens produced from each batch included group A or group B. There are six specimens in each group. All samples were consolidated using a high-frequency vibrating table. Samples were produced by placing concrete into a $100 \times 100 \times 400$ mm mold. These concrete specimens were cured at more than 95% relative humidity (RH) and a temperature of 20°C plus or minus 2°C. The specimens were demolded after eight hours. After demolding, the specimens were then immediately placed into the test chamber of MDT. The specimens were moved into the chamber maintained at 18.5°C and kept for another hour in order to maintain constant temperature in each part of the samples. The initial value of displacement sensor and load cell was determined before applying the temperature cycle.

It takes 24 hours to complete a cycle of temperature variation, consisting of heating and cooling, from 18.5°C to 35°C and back. The rate of change is 1.4°C in the temperature cycle. The average of daily maximum/minimum temperature is 35°C/18.5°C in July from 1951 to 2000 in Northern China [19, 20]. The average is the mean value of daily maximum/minimum temperature in July's 31 days. The time interval between daily minimum temperature and maximum temperature is about 10~12 hours in summer. 12 hours is used in this study.

Two cycles taking 48 hours were investigated in this work. The interval of measuring temperature and strain of specimens is two minutes. The weight data of samples were collected before the temperature cycle, at the termination of the first cycle and the second.

3. Numerical Model

3.1. Modeling. Based on thermoelastic theory, finite element simulation was performed to analyze the effect of temperature variation on concrete strain by using the software ABAQUS. Thermal strain is calculated by numerical modeling of concrete specimen in order to exclude its effect on shrinkage. Shrinkage is not considered in this model. It can be assumed that the temperature in each part of the model is identical because of the small cross-sectional size. As a result, this model can be simplified to a plane strain problem. The two-dimensional finite element model of $0.1\,\text{m} \times 0.4\,\text{m}$ is shown in Figure 3.

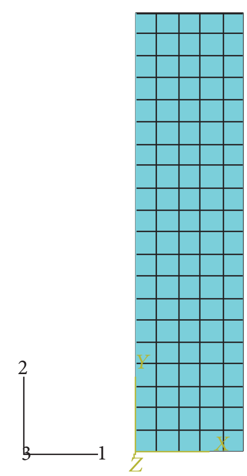


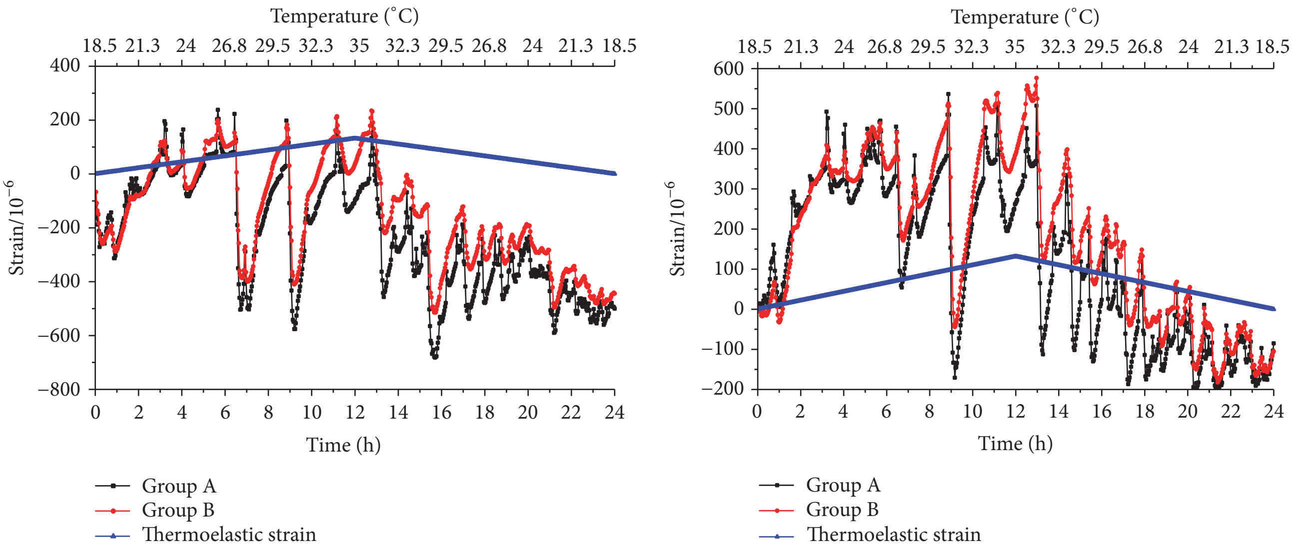
Figure 3: Finite element model of concrete specimen.

3.2. Boundary Conditions. According to the experimental design, the initial temperature being assigned to the model is 18.5°C. The cycle of temperature variation is from 18.5°C to 35°C and back within 24 hours. The rate of heating and cooling is 1.4°C. The first boundary condition was used in the model based on heat transfer theory. This means that the temperature surrounding the model is known, which is equal to internal temperature of the test chamber. The vertical displacement at the bottom of model is 0.

3.3. Parameter Selection. The following parameters were considered for this model: thermal conductivity = 3.0 W/(m·K), specific heat = 1000 J/(kg·°C), thermal expansion coefficient = 8×10^{-6}, density = 2400 kg/m^3, and Poisson ratio of concrete = 0.18 [21, 22].

4. Results and Discussion

4.1. Evolution of Shrinkage of Early Age Concrete. The strain measurements are illustrated in Figure 4. The data points



(a) The first cycle of temperature variation

(b) The second cycle of temperature variation

Figure 4: Strain of specimens.

indicate the average of six specimens. The data of thermoelastic strain is obtained through the numerical model. Volume expansion is by definition positive and volume reduction is negative.

As shown in Figure 4, the thermoelastic strain gradually changes. There are sharp fluctuations in the strain data readings. For instance, between 6 and12 hours in the first cycle, the strain goes +100, −500, 0, −500, and +50 μ. These fluctuations may be caused by autogenous shrinkage and drying shrinkage. Autogenous shrinkage is the macroscopic volume reduction of cementitious materials when cement hydrates after initial setting [23]. Drying shrinkage is produced by capillary tension, solid surface tension, and withdrawal of hindered adsorbed water and interlayer water from cement gel [23, 24].

The deformation curve of group A is roughly similar to group B, but there are still differences. The absolute values of shrinkage strain of group A are larger than group B, but the swelling strain of the former is less than the latter. Considering that the water-cement ratio of group A is smaller than group B, this is mainly due to the fact that lower the w/c ratio leads to denser concrete microstructure and smaller capillary aperture. And the internal relative humidity is going to quickly decrease, resulting in larger shrinkage. The w/c ratio not only influences the course of shrinkage. It is clear from experiments that it greatly influences the microscopic structure of the hydrated cement grout and concrete [25]. In high w/c concrete, The interfacial transition zone between the aggregate and cement matrix is highly porous and is filled with large crystals of lime [25, 26]. Investigations from [27] also show that increasing the water-cement ratio reduces the heat generated per unit volume by either reducing the volumetric cement content or its early age reactivity, and reduces autogenous shrinkage by increasing the interparticle spacing between grains in the three-dimensional microstructure.

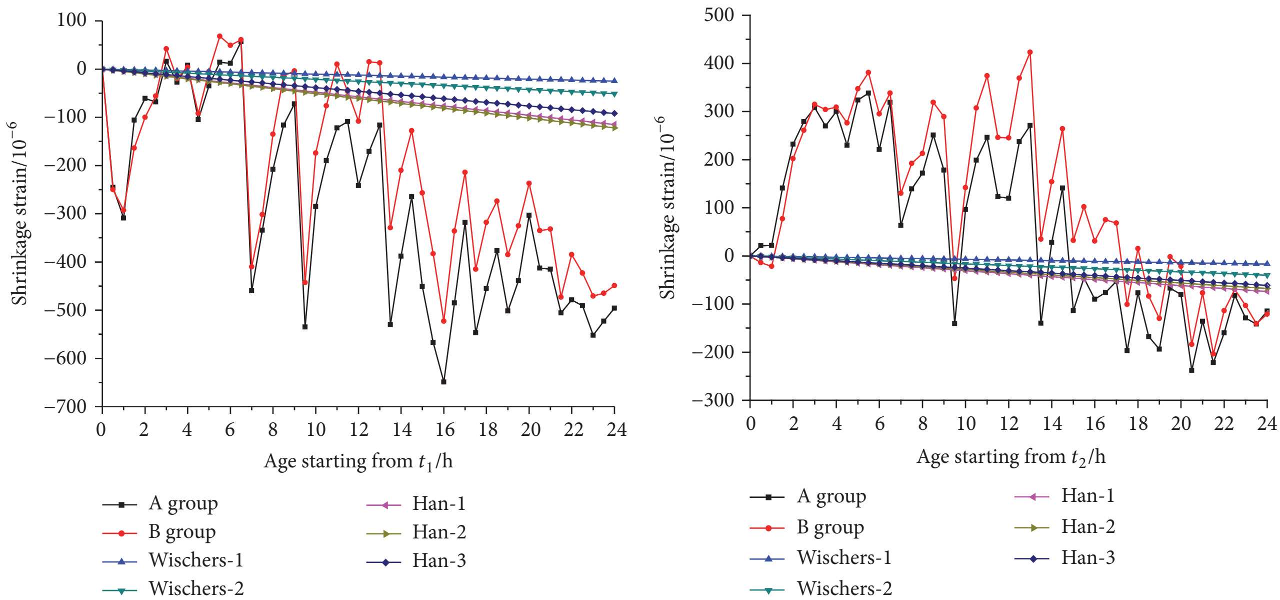
The growth rate of autogenous shrinkage and drying shrinkage gradually reduces, with the increase in concrete age and the progress of hydration [23, 24]. So the measured shrinkage strain of the first cycle is greater than the second cycle. As tests reported [28], more than one-half of the final autogenous shrinkage occurs during the first 24 hours after mixing of the high strength concrete.

The variation trend of strain is swelling in the process of warming and shrinking during cooling. There are several alternations of expansion and shrinkage. The strain differences are up to 600 μ or more. This is caused by: (1) the response of internal temperature of concrete to ambient temperature is the process of heat conduction with a certain lag. (2) The moisture loss in concrete, which consists of capillary water, adsorbed water and interlayer water, will lead to drying shrinkage. The loss of interlayer water in tobermorite gel of cement paste increases as temperature rises [29, 30]. (3) The diffusion rate of temperature in concrete is greater than drying shrinkage by about 1000 times [31].

Figure 4 demonstrates that the rate of change of strain increase increasing (or decreasing) is roughly the same during two cycles. This was produced by constant gradient of heating and cooling in the test chamber. The rate of temperature variation in the test chamber is different from the diffusion rate of temperature in concrete, resulting in the gap between the two groups.

The average weights of the specimens are shown in Table 2. w_0 means the average weight of each group at the start of the experiment. w_1 or w_2 is the average weight at the end of the first cycle or the second cycle.

It can be seen that air temperature variation leads to water loss and weight reduction. With the growth of age, the rate of change of specimen weight reduces. There are capillary water, adsorbed water, interlayer water and chemically combined water in hardened cement paste. Except that chemically combined water in the hydrated crystals cannot be lost, the remaining water can dissipate when the humidity is below a certain value [29]. After thermodynamic equilibrium



(a) The first 24 hours (b) The second 24 hours

FIGURE 5: Comparison of shrinkage strain.

TABLE 2: Average weights of specimens (kg).

Specimen number	w_0	w_1	$\Delta_1 = w_1 - w_0$	w_2	$\Delta_2 = w_2 - w_1$	$\Delta_1 + \Delta_2$
Group A	10.338	10.304	0.034	10.289	0.015	0.049
Group B	10.215	10.178	0.037	10.158	0.020	0.057

TABLE 3: Test parameters and results.

Number	w/c	c (kg/m^3)	Geometry (mm)	t_0 (days)	T (°C)	H (%)		t (days) 0	1	3
Wischers-1	0.48	325	C 150 × 600	0.83	20	65		0	−25	−42
Wischers-2	0.40	400	C 150 × 600	0.42	20	65		0	−51	−91
Han-1	0.316	475	P 100 × 400	0.67	20	50	Strain (1×10^{-6})	0	−115	−189
Han-2	0.316	475	P 100 × 400	0.67	20	50		0	−122	−190
Han-3	0.316	475	P 100 × 400	0.67	20	50		0	−92	−153

has been established in the pores of the cement paste, free capillary water evaporates first, followed by the water from the adsorption surface layers of the walls of the pores [32]. The loss of this water produces stresses which cause the concrete to shrink. The early age shrinkages increase with increasing moisture loss, approximately in a linear manner, for the concrete with the same curing type [30, 33].

4.2. Effect of Consecutive Temperature Variation. The impact of atmospheric temperature on shrinkage was studied by comparing with others' test (Wischers [34] and Han [35]) on shrinkage strain under constant temperature and humidity. The test parameters and results by Wischers and Han are shown in Table 3. W/c is water-cement ratio and c is the quality of cement per cubic meter of concrete. Geometry is the size of concrete specimen; C stands for cylinder and P means prism. t_0 is the concrete age at the beginning of test and t is concrete age. T is temperature. H is humidity. The measured strain of this paper and others' data is illustrated in Figure 5.

As presented in Figure 5, the obtained strain shows sudden spikes and the referenced models are nearly linear. The shrinkage strain of this study is larger than strain from Wischers's and Han's in the first 24 hours. The strain differences are up to 500 μ. Autogenous shrinkage is influenced by the temperature change in concrete [36]. The possible reason is that the microstructure evolution and apparent activation energy are influenced by temperature [37]. Compared to thermal deformation and drying shrinkage, autogenous shrinkage accounts for the foremost significance in volume change components of concrete at early ages [38].

There is an equilibrium of humidity between concrete and ambient air. Both a humidity decrease and temperature rise will lead to water loss. During concrete drying, the loss of capillary water causes shrinkage. When the humidity is low, adsorbed water and interlayer water will dissipate in order. The contact force between capillary water and solid is very small in concrete. The relationship between adsorbed water, interlayer water, and solid cement is physical adsorption. With continued drying, the difficulty of water loss increases; the rate of shrinkage gradually reduces under consecutive temperature variation. This may explain why the influence of air temperature variation on shrinkage strain is enormous.

5. Conclusions

The time-dependent shrinkage of early age concrete subjected to air temperature variation is presented. The results indicate the following:

(1) There are several sharp fluctuations in the strain of early age (within the first 3 days) concrete. The magnitude of shrinkage is up to 600 μ.

(2) With the increase of age and development of hydration, shrinkage strain of concrete decreases and expansion strain increases. For the impact of autogenous and drying shrinkage, absolute values of shrinkage strains affected by air temperature variation are higher than thermal strains in the first two days.

(3) Daily temperature changes lead to water loss in early age concrete. The difference in shrinkage strain under temperature variation or constant temperature is up to 500 μ.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This paper is sponsored by National Science Foundation of China (51408083 and 51508064), Postdoctoral Science Foundation of China (2014M562287), Frontier and Applied Basic Research Projects of Chongqing (cstc2014jcyjA30018 and cstc2016jcyjA0128), Postdoctoral Science Foundation of Chongqing (Xm2014094), and CREEC (14126146).

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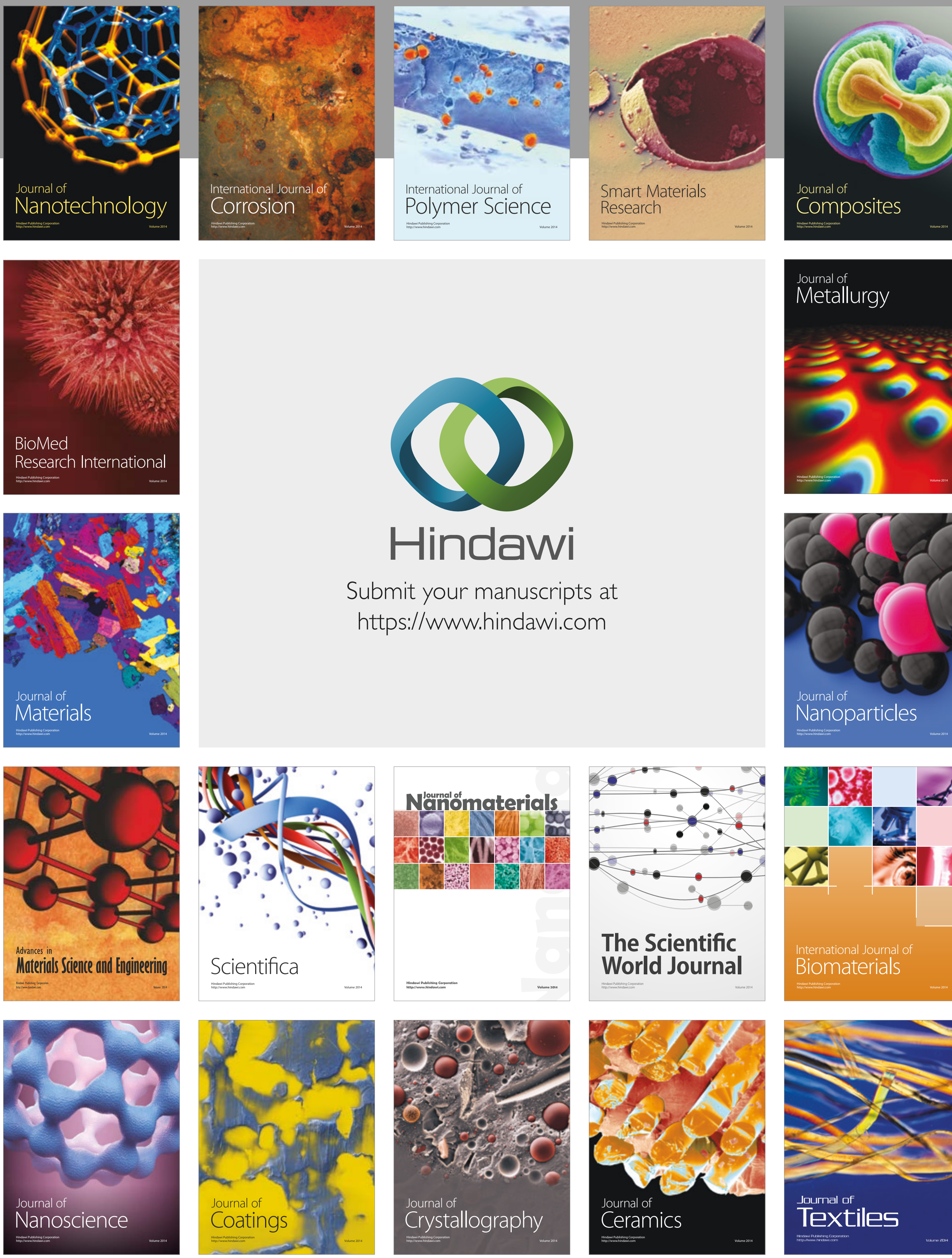
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