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Research Article

Behavior of HPC with Fly Ash after Elevated Temperature

Huai-Shuai Shang[1,2] and Ting-Hua Yi[3]

[1] *School of Civil Engineering, Qingdao Technological University, Qingdao 266033, China*
[2] *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China*
[3] *Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023, China*

Correspondence should be addressed to Huai-Shuai Shang; shanghuaishuai@yahoo.com.cn

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For use in fire resistance calculations, the relevant thermal properties of high-performance concrete (HPC) with fly ash were determined through an experimental study. These properties included compressive strength, cubic compressive strength, cleavage strength, flexural strength, and the ultrasonic velocity at various temperatures (20, 100, 200, 300, 400 and 500°C) for high-performance concrete. The effect of temperature on compressive strength, cubic compressive strength, cleavage strength, flexural strength, and the ultrasonic velocity of the high-performance concrete with fly ash was discussed according to the experimental results. The change of surface characteristics with the temperature was observed. It can serve as a reference for the maintenance, design, and the life prediction of high-performance concrete engineering, such as high-rise building, subjected to elevated temperatures.

1. Introduction

High-performance concrete (HPC) [1–5] is a complex system of materials that perform most effectively when placed in severely aggressive environments. It has found widespread usage in construction application including bridges, tunnels and high-rise building. Concrete in normal conditions is a versatile, resistant, and durable construction material. However under several physical and chemical processes as well as certain environmental conditions, it may deteriorate in a short period of time. As the use of high-performance concrete becomes common, the risk of exposing it to elevated temperatures also increases. The behavior of high-performance concrete under elevated temperatures differs from that of plain concrete. To be able to predict the response of structures employing high-performance concrete during and after exposure to high temperature, it is essential that the strength properties of high-performance concrete subjected to high temperatures should be clearly understood.

Fly ash (FA) is a byproduct of thermal power stations [6]. It is estimated that approximately 600 million tons of FA are available worldwide now, but at present, the current worldwide utilization rate of FA in concrete is about 10% [7]. FA is one of the most common concrete ingredients due to their pozzolanic properties [7, 8]. In the past two decades, considerable attention has been given to the use of FA as a partial replacement for cement in the production of high-performance concrete.

Kim et al. [9] studied the effect of elevated temperatures ranging from 20°C to 700°C on the mechanical properties of high-strength concrete of 40, 60, and 80 MPa grades. Poon et al. [10] investigated the effects of elevated temperatures on the compressive strength of fiber reinforced high-performance concrete. The results showed that, after exposure to 600 and 800°C, the concrete mixes retained, respectively, 45% and 23% of their compressive strength, on average. Khaliq and Kodur [11] present the effect of temperature on thermal and mechanical properties of high-performance self-consolidating concrete. In particular, there is a great risk that HPC spalls at elevated temperature compared with plain concrete [12, 13]. Due to the poor fire resistance of HPC [14, 15], it should be recommended that the use of HPC should be limited in some cases unless future research is carried out to study and solve this problem. Thus, the investigation on

Table 1: Mix proportions and major parameters of concrete.

Strength level	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Water-reducing agent (kg/m^3)	Slump (cm)
C60	470	616	1095	175	94.5	6.77	24
C50	434	640	1080	185	91.0	5.81	25

performance of HPC subjected to elevated temperature is of great significance. This paper presents an experimental study of high-performance concrete with characteristic compressive strength of about 50 MPa and 60 MPa after 20°C, 200°C, 300°C, 400°C, and 500°C according to the GB/T 50081-2002 (standard for test method of mechanical properties on ordinary concrete) [16]. The compressive strength, cubic compressive strength, cleavage strength, flexural strength, and the ultrasonic velocity of HPC with fly ash were measured. The objective of this study is to increase the insight of the mechanical behavior of high-performance concrete with FA after exposure to elevated temperatures.

2. Experimental Procedures

2.1. Materials and Mix Proportions. To produce such a better quality of concrete, chemical and mineral admixtures such as fly ash, slag cement, and water reducers are commonly used in the field construction to increase the concrete strength. In this experimental study, two high performance concrete mixes have been studied, one high-performance concrete with a characteristic compressive strength of about 50 MPa, denominated C50, and another high-performance concrete, designed to achieve a compressive strength of about 60 MPa, denominated C60. In this experimental study, samples were made in a variety of trial concrete mix proportions and tested to determine the proportion which provided the required strength. Local materials were utilized. A Chinese standard (GB175-99) [17] 525 Portland cement (which has standard compressive strength of 52.5 MPa at the age of 28 days) was used. Natural river sand with fineness modulus of 2.6 was used. Coarse aggregate was a crushed stone with diameter from 5 mm to 20 mm. FA was applied to the mixture to the proportion of 20% (C50) and 21% (C60) of cement weight. Due to low water-cement ratios of the concrete mixtures, a water-reducing agent was employed. The mixture proportions and the major parameters for the two batches are listed in Table 1.

2.2. Samples and Testing Programs. In this study, all mixes were elaborated using a 0.25 m^3 horizontal forced action mixer. The mixing procedure was as follows: first the coarse aggregate, then fine aggregate, and the cement were loaded with the FA. These components were mixed for about 1 minute and after it the water with water-reducing agent was added in one minute and the mixing continued for another 3 minutes and the process finished.

Concrete prisms with size of 100 mm × 100 mm × 100 mm to determine the compressive strength (in order to eliminate the restraint on the loading surfaces, the friction-reducing pads were placed between the platens and the specimens for all tests. The pads consist of three plastic membranes with three layers of butter between them [18]), cubic compressive strength, cleavage strength, and the ultrasonic velocity and 100 mm × 100 mm × 400 mm to determine the flexural strength were casted in steel molds. During casting, compaction was achieved by placing the molds on a vibrating table and vibrating it at a frequency of 40 HZ for one second. All cast specimens were compacted through external vibration and demoulded 24 h later. Thereafter, all the specimens were cured in a moisture room with a condition of 20 ± 3°C and 95% RH for 27 days. At 28 days, the specimens were transported to the normal environment. At 120 days, the specimens were ground and prepared for testing. The two sides of specimen were ground to ensure that the specimen had flat edges and right angle corners. The final ground surface finish was within ±0.01 mm.

The tests of high temperatures were performed in the high temperatures testing apparatus in State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The high temperatures testing apparatus was a box-type electric furnace, as shown in Figure 1. The 100 mm cubic specimens were elevated to the peak temperatures of 200°C, 300°C, 400°C, and 500°C at a heating rate of 10°C/min, respectively. Then 6 h was maintained after the peak temperature was reached. The cooling time in electric furnace was about 24 h, and then the specimens were taken out and cooled naturally to room temperature.

The compression testing machine used for this experiment was a machine with a maximum capacity of 100 KN, as shown in Figure 2. Compressive testing of the test specimens was done in accordance with (standard for test method of mechanical properties on ordinary concrete) GB/T 50081-2002 [16]. The maximum loading force was always applied to the surfaces that were perpendicular to the cast surfaces. The testing of the specimens can be carried out in stress-controlled mode, and all specimens were tested at a loading speed of 20.0 MPa per minute.

3. Results and Discussions

3.1. Failure Modes. Figures 3(a) and 3(b) show the failure modes of HPC under uniaxial compression with and without friction-reducing pads, respectively. The column-type fragments were observed for HPC under uniaxial compression with friction-reducing pads. The tensile strain will be caused in the direction of free surface because of the action of compressive load and the crack forms when the strain was larger than the ultimate tensile strain of the specimen. It was noticed that the cracks on the loaded surface have a random direction because of the influence of coarse aggregates.

Figure 1: Box-type electric furnace.

Figure 2: Compression testing machine.

The friction between loading plate and loading surface hinders the development of tensile strain close to loading surface. So the cracks will not form or the number of cracks will be reduced near the loading surface. The restriction effect of the friction between loading plate and loading surface on the development of tensile strain at the middle of the specimen is little. So the cracks near the middle of specimen will form. And the taper-type fragments were observed for HPC under uniaxial compression without friction-reducing pads.

The splitting tensile strain along the unload plane(s) was the cause of failure for both. It was obvious that the influence of elevated temperature on HPC did not change the tensile splitting mode from occurring. There was no great change in the failure modes for HPC after the action of elevated temperature.

Table 2: The cubic compressive strength of HPC at different ages (MPa).

Time (d)	3	7	14	21	28	60	90	120
C50	43.00	49.93	57.01	61.20	62.71	65.75	66.83	68.17
C60	46.73	54.27	61.97	66.52	68.17	71.47	72.64	74.10

Table 3: The compressive strength and cubic compressive strength of HPC at elevated temperature (MPa).

Concrete		Temperature (°C)				
		20	200	300	400	500
C50	f_c	33.93	33.6	36.0.7	29.33	26.53
	f_{cu}	55.16	54.40	54.67	52.00	44.37
C60	f_c	51.60	50.33	42.0	44.73	37.13
	f_{cu}	68.17	66.62	63.51	67.0	55.53

3.2. Strength

3.2.1. The Cubic Compressive Strength and Compressive Strength. The compressive stress was calculated by dividing the compressive load by the area of loading section (0.01 m^2). For each mixture, a minimum of three specimens were tested at 3, 7, 14, 21, 28, 60, 90, and 120 days. Tables 2 and 3 provide the basic physical properties cubic compressive strength and compressive strength for the high-performance concrete at different ages, respectively.

The C50 and C60 concrete developed a 3-day compressive strength of 43.0 MPa and 46.73 MPa, respectively. (These high values are mainly due to the high fineness of the cement used. However, the 3-day compressive strength of the concrete made with the fly ash is still adequate for most of the concrete structures for formwork removal at three days.) At 7 days, the compressive strength of the C50 concrete approached that of the control concrete (50 MPa), and at 14 days it (57.01 MPa) surpassed design value of strength (50 MPa). While for C60 concrete, the compressive strength surpassed design value of strength (60 MPa) at 21 days. In fact, the 28-day compressive strength of the C50 and C60 concrete was 22% and 11% higher than the design value of strength, respectively.

The variation of the cubic compressive strength and compressive strength with time for two types of high-performance concrete is shown in Figure 4.

The variation of the cubic compressive strength and compressive strength with temperature is given in Table 3 for two types of high-performance concrete. In two types of HPC, temperature has a slight bearing on the cubic compressive strength of concrete in the temperature range from 20°C to 300°C. Initially, as the temperature increased to 200°C, the strength decreased compared to the original strength. With further increase in temperature, the specimens recovered part of their strength at 300°C. The strength at 300°C is about 99.1% and 93.2% of the original strength (at 20°C) for C50 and C60, respectively. During the temperature range of 400°C to 500°C, the strength drops sharply, reaching a low level of 80.4% and 81.5% of initial strength for C50 and C60, respectively. The cubic compressive strength of HPC with temperature is shown in Figure 5.

(a) (b)

Figure 3: Failure modes of HPC under uniaxial compression.

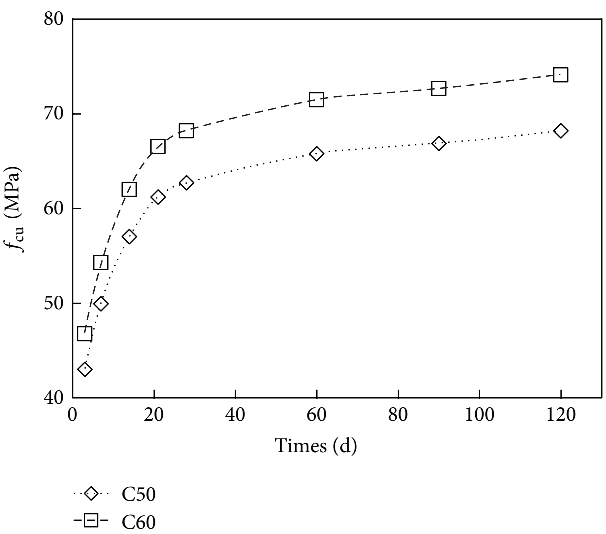

Figure 4: The variation of the cubic compressive strength with time.

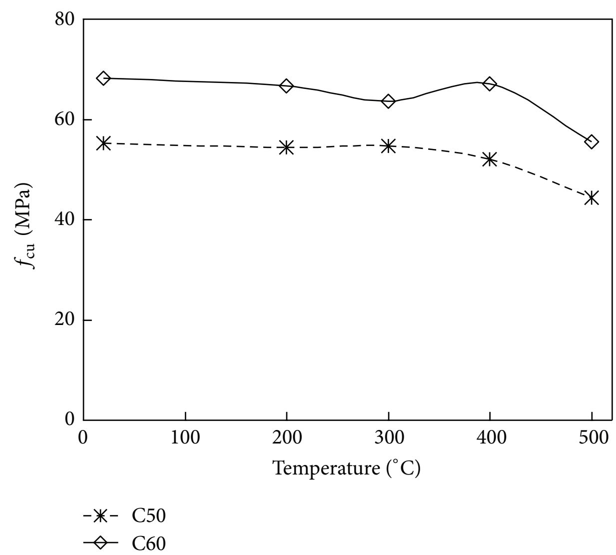

Figure 5: Cubic compressive strength of HPC at elevated temperature.

In the temperature range of 20°C to 200°C, the change of compressive strength is slight. Initially, as the temperature increased to 200°C, the strength decreased by 1.0% and 2.5% percent of the original strength. In the temperature range of 200°C to 300°C, the compressive strength of C50 increases to 1.06 times the original strength, while the compressive strength of C60 drops to 81.4% of the original strength. In the temperature range of 400°C to 500°C, all two types of HPC lose their strength at a faster rate, and the strength drops sharply, reaching a low level of 78.2% and 72.0% of initial strength for C50 and C60, respectively. At these temperatures, the dehydration of the cement paste results in its gradual disintegration. Since the paste tends to shrink and aggregate expands at high temperature (differential thermal expansion at temperatures above 100°C), the bond between the aggregate and the paste is weakened, thus reducing the strength of the concrete. Figure 6 gives the change of compressive strength of HPC with temperature. This was different from the result in [19]. The test results in [19] indicated that each temperature range had a distinct pattern of strength loss.

3.2.2. The Cleavage Strength and Flexural Strength. Cleavage strength and flexural strength of the concrete are given in Tables 4 and 5. The loading mode of cleavage test meeting (Testing Code of Concrete for Port and Waterwog Engineering) [20] was used. The 120-day cleavage strengths were 3.80 and 4.47 MPa for C50 and C60, respectively. The 120-day flexural strengths were 7.80 and 8.38 MPa for C50 and C60, respectively.

In the temperature range of 20°C to 200°C, temperature has a slight bearing on the cleavage compressive strength of two types of HPC concrete. The cleavage strength at 300°C

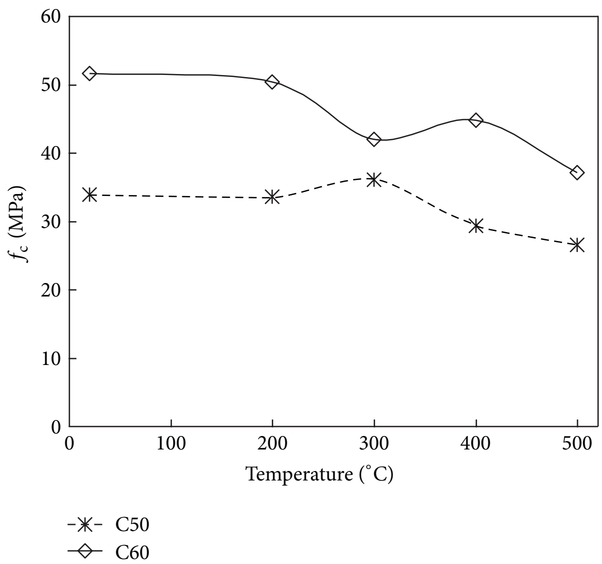

Figure 6: Compressive strength of HPC at elevated temperature.

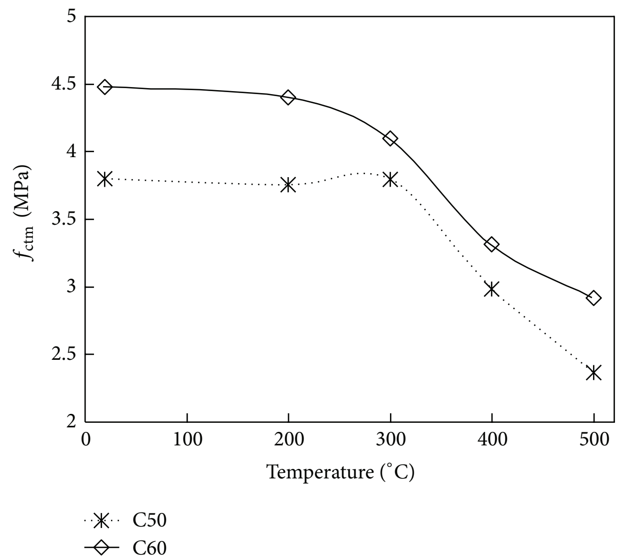

Figure 7: Cleavage strength of HPC at elevated temperature.

Table 4: The cleavage strength of HPC at elevated temperature (MPa).

Concrete	Temperature (°C)				
	20	200	300	400	500
C50	3.800	3.756	3.790	2.984	2.362
C60	4.474	4.401	4.098	3.310	2.916

Table 5: The flexural strength of HPC at elevated temperature (MPa).

Concrete	Temperature (°C)				
	20	200	300	400	500
C50	7.800	6.961	5.404	4.644	4.290
C60	8.380	8.253	6.565	5.834	5.378

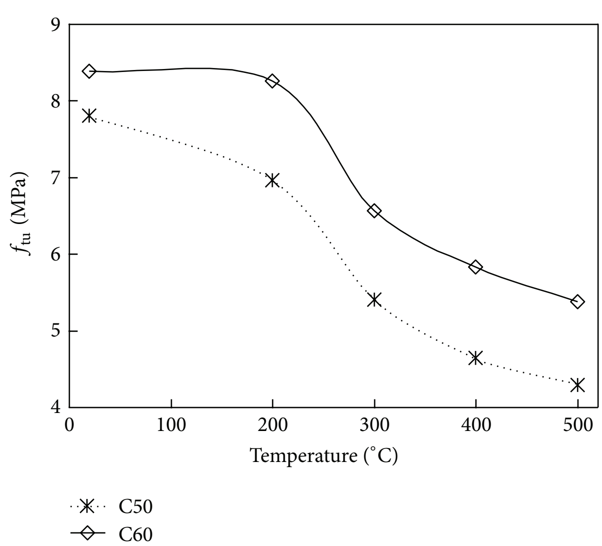

Figure 8: Flexural strength of HPCat elevated temperature.

of C50 and C60 is about 99.7% and 91.6% of the original strength (at 20°C), respectively. Above 300°C, the two types of HSC lose their cleavage strength at a faster rate. The cleavage strength at 500°C of C50 and C60 is about 62.2% and 65.2% of the original strength (at 20°C), respectively. The variation of the cleavage strength with temperature is shown in Figure 7.

Flexural strength is the most commonly used procedure to evaluate the toughness, and three-point bending tests are also carried out. For each mixture, the flexural strength was determined on two prisms each at elevated temperature (20, 200, 300, 400, and 500). In the temperature range of 20°C to 200°C, the change of fleural strength is slight. Initially, as the temperature increased to 200°C, the strength decreased 10.8% and 1.5% of the original strength for C50 and C60, respectively. As the temperature increased from 200°C to 500°C, the flexural strength dropped sharply compared to the original strength. Overall, HPC at elevated temperatures loses a significant amount of its compressive strength above 200°C and attains a strength loss of about 45.0% and 35.8% at 500°C for C50 and C60, respectively. Figure 8 shows the flexural strength of HPC with elevated temperature.

3.3. The Ultrasonic Velocity. A lot of structures, like bridges, tunnels, dams, buildings, and others, were constructed with concrete material. During the life cycle of these structures, degradations can occur under mechanical, thermal, or chemical stresses. These often lead to the development of porosity, microcracks, and cracks in the material. Knowing the concrete structure state to prevent or repair damage is needed and so the nondestructive characteristic is an important stake, the ultrasonic method is often proposed. Ultrasound (sonic (frequency: from 20 to 20,000 Hz) human hearing range, subsonic (frequency: <20 Hz), and ultrasonic (frequency: >20,000 Hz)) is sound above the human hearing

Table 6: Loss of the ultrasonic velocity of HPC at elevated temperature.

Concrete	Temperature (°C)				
	200	300	400	500	500
C50	100	85.9	81.8	76.1	61.2
C60	100	92.2	80.8	69.3	58.5

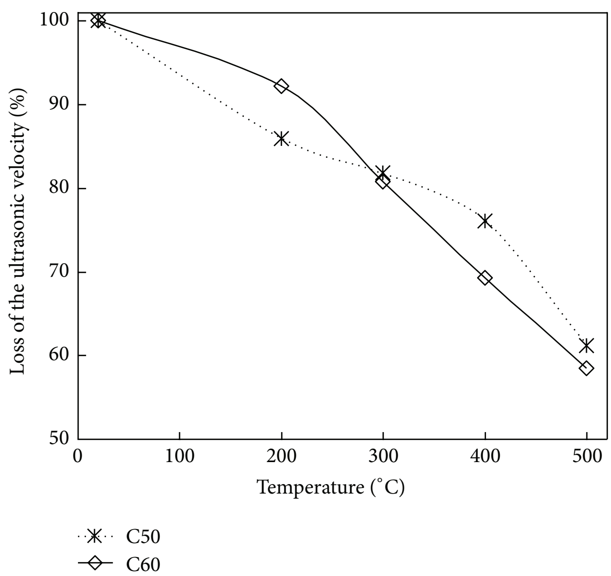

Figure 9: Loss of the ultrasonic velocity at elevated temperature.

range. Ultrasonic velocity is the speed in which sound travels through a given material. It is affected by density and elasticity. Velocity remains constant in a given material.

Table 6 gives the decreasing percentage of the ultrasonic velocity with temperature for high-performance concrete. As seen from Table 6 the ultrasonic velocity decreased as temperature. The ultrasonic velocity at 500°C of C50 and C60 is about 61.2% and 58.5% of the original velocity (at 20°C), respectively. Loss of the ultrasonic velocity of HPC with elevated temperature is shown in Figure 9.

3.4. The Surface Characteristics and Spalling. The induction of color change in concrete is associated with maximum temperature of exposure and loss in mechanical properties. By combining the changes of strength, color, and temperature during fire, the retained strength of concrete can be inferred primarily. This will provide some reference for concrete structure in practice. It can be said that, in the buildings damaged by fire, by examining the color of concrete surface, we can have some ideas about the change in the concrete strength [21]. So the change of color was observed; according to the visual inspection, a variation with color is revealed, and for concrete subject to 300°C, color does not change and it is gray, off-white when the concrete is exposed to temperature of between 400°C and 600°C.

Tanyildizi and Coskun [19] investigated the surface cracks; the results are as follows: the surface cracks started to appear at round 400°C, and continued to grow till the final rise in temperature up to 800°C. The crack decreased with the increase of fly ash content and at the same time increased with the increase of temperature. And no surface cracks were observed in the experiment.

However spalling has been identified as a problem with HPC by other researchers [22, 23]. But no evidence of spalling was founded during the simulated fire tests for HPC.

4. Conclusion

Based on the experimental work in this study and the discussion about test results, the following conclusions can be drawn

(1) The thermal properties, at elevated temperatures, exhibited by high-performance concrete are similar to those of plain concrete.

(2) The failure modes of HPC under uniaxial compression with and without friction-reducing pads were column-type fragments and taper-type fragments, respectively. The splitting tensile strain along the unload plane(s) was the cause of failure for both.

(3) Above 300°C, the two types of HSC lose their cleavage strength at a faster rate. The cleavage strength at 500°C of C50 and C60 is about 62.2% and 65.2% of the original strength (at 20°C), respectively. As the temperature increased from 200°C to 500°C, the flexural strength dropped sharply compared to the original strength.

(4) The present study was undertaken to establish the thermal properties of HPC at elevated temperatures. The data can be used to develop mathematical models to predict the fire resistance of HPC structural members.

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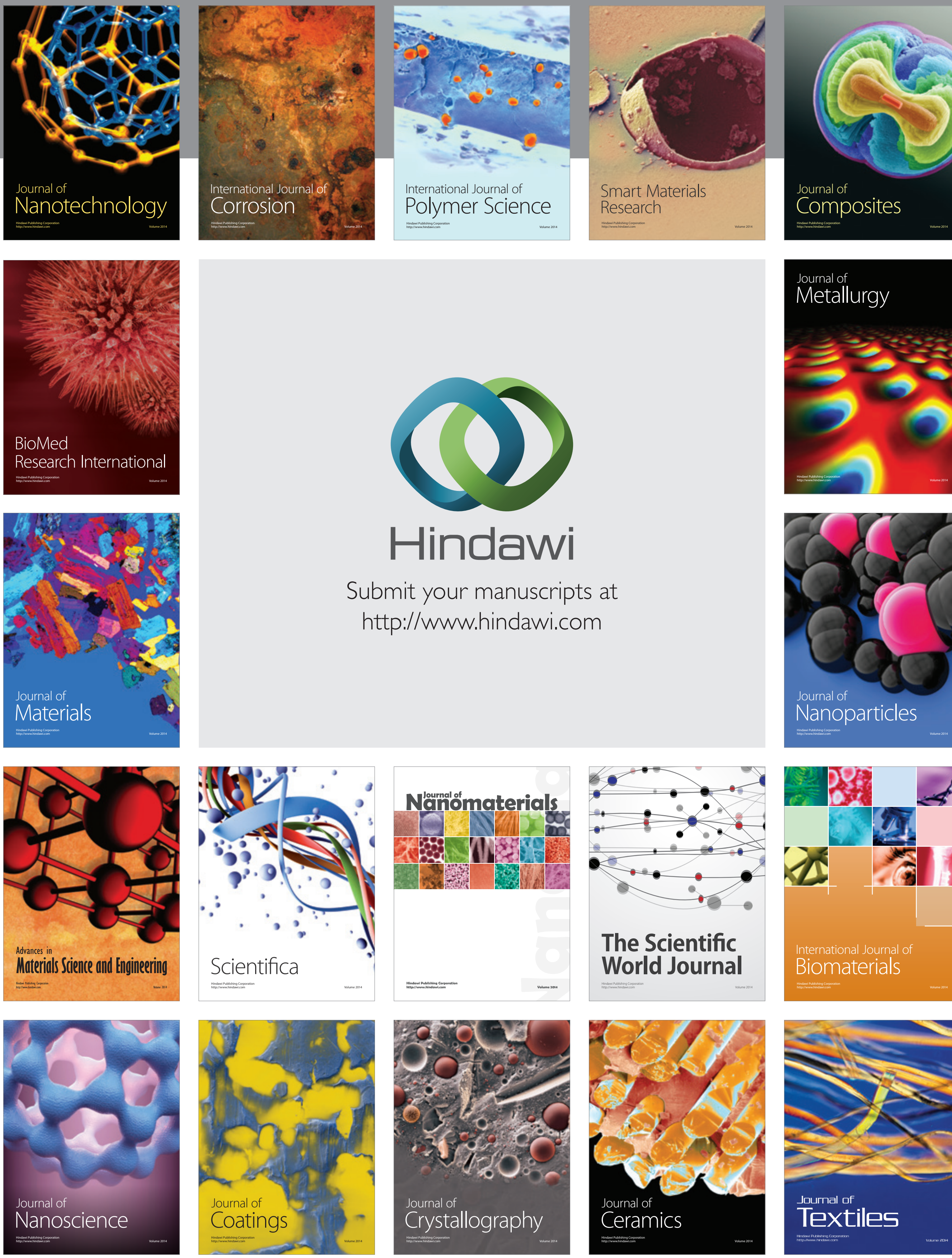
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