Hindawi
Advances in Materials Science and Engineering
Volume 2018, Article ID 9160801, 9 pages
https://doi.org/10.1155/2018/9160801

*Research Article*

# Influences of Environmental Conditions on the Cracking Tendency of Dry-Mixed Plastering Mortar

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Received 3 January 2018; Accepted 13 February 2018; Published 2 April 2018

Academic Editor: Robert Cerný



Cracking tendency is one of the important performances of dry-mixed plastering mortar (DMPM). Environmental condition is a key factor to affect the cracking tendency of DMPM. For the purpose of evaluating the cracking resistance of DMPM and revealing the influence of environmental conditions on the cracking tendency of DMPM, a series of experiments were performed on restriction-induced cracking behaviors as well as free shrinkage, water loss, and mechanical properties of DMPM. The restricted shrinkage tests were based on ring tests and plate experiments. The results showed that the initial drying age exhibits significant influence on the cracking tendency of DMPM, and there was a stress balance period when the initial drying age was 2 days. But, the phenomena cannot be observed when the initial age was 3 d, 5 d, and 7 d. In order to eliminate the cracking tendency of DMPM, it should avoid water loss from the plaster layer during construction in practical engineering, especially, before initial drying ages.

## 1. Introduction

Compared with traditional plaster mortars, dry-mixed plaster mortar (DMPM) is a more environmentally friendly building material by reducing air pollution and waste production on construction sites. It can reduce carbon dioxide emissions, help the construction site keep clean, and allow for more flexibility in storage space for materials while reducing cement redundancy after the cement finishing is completed. Moreover, this new and advanced construction material is convenient to deploy and transport, delivers product with stable quality, helps us to facilitate construction, and saves materials [1–6]. There are many causes resulting in cracking of concrete, and shrinkage is of the upmost importance among them [7–11]. If the concrete is restrained, when the tensile stress induced by drying shrinkage exceeds the tensile strength, cracking would happen [9, 12–15]. By the same token, shrinkage cracking is also an important problem in wall plastering mortar. There are a variety of wall plastering mortar cracking causes including thermal gradients, moisture gradients, and attacks from external and internal environments [16]. Drying shrinkage, which is one of the major causes of cracking of cement mortar, is related to the water loss from mortar. The early age cracking behavior is very complex because it not only depends on the manifestation rate and magnitude of the shrinkage of the hardened cement paste with ages but also other factors such as strength development, degree of restraint, stress relaxation, and shape of the structure.

Currently, many investigators focus on revealing the mechanisms of cracking by several kinds of experiments and developing prediction models of crack development [12, 16–18]. The ring test is a commonly used method for assessing the potential of shrinkage cracking. Moon and Weiss used the ring test to assess the restrained shrinkage behavior of mortar and concrete under various conditions [5, 8, 9, 12, 17, 19]. They proposed revisions to the estimation equations developed in previous studies to consider the

Table 1: Mix proportions of dry-mix plaster mortar (g).

| Grade | Cement | Thickening powder | Fly ash | Water | Sand |
|---|---|---|---|---|---|
| DMPM 15 | 160 | 7 | 23 | 34.2 | 810 |

Figure 1: Water loss rate test of the DMPM prism specimen.

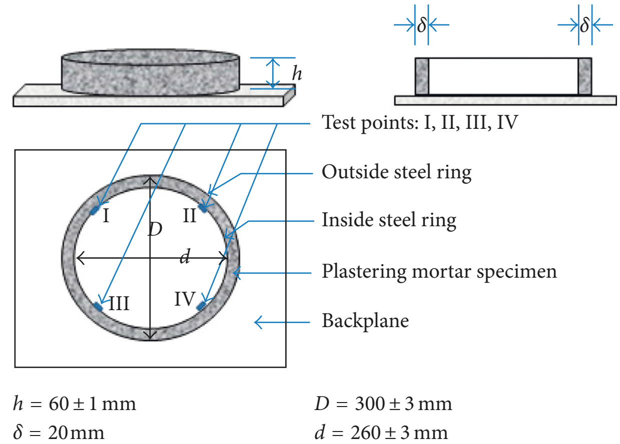


Figure 2: Schematic diagram of the ring restraint test device.

changes in stress in the cross section because of differential drying shrinkage. These stress changes were caused by different levels of ambient relative humidity, and the position of the cross section of the concrete ring [7, 19].

In this paper, the ring tests were performed to qualitatively assess shrinkage and cracking tendency of DMPM under different environmental conditions, including different wind speed, types of subbase, and initial drying age. In addition, free shrinkage and tensile strength of DMPM specimens were performed with the same cross section in the same environmental condition.

## 2. Experiment Program

*2.1. Raw Materials and Mixture Proportion.* Cement type used in this study is P·O 42.5 in accordance with Chinese GB 175-2007, and bentonite was used as a thickening powder agent. Grade I fly ash in accordance with Chinese GB/T 1596-2005 was employed as mineral admixture. The fineness modulus of natural river sand was 2.3, and the rate of water and dry material was 0.18. Table 1 shows the mix proportions of dry-mix plaster mortar.

*2.2. Water Loss Rate.* In order to study the relationship between drying shrinkage and water loss of mortar specimens, the free shrinkage and the water loss rate of a pyramid specimen were tested, respectively. The size of specimen was 40 mm × 40 mm × 160 mm. The specimens were placed in a 20 ± 2°C, 50 ± 5% RH environment at initial drying age.

It is generally known that the wind can promote water evaporation. In order to investigate the influence of wind environment on DMPM, the water loss rate of the pyramid prism specimen was tested under wind speed at 0 m/s, 4 m/s, and 8 m/s. Figure 1 shows the method for testing the water loss rate of the pyramid prism specimen under different wind speeds.

*2.3. Restrained Shrinkage Test A: Ring Test.* Due to its practicability, and easy operation to measure strain or stress, the "ring test" was commonly used to assess the potential for shrinkage cracking. The device consists of a mortar ring specimen that was cast around a steel concentric ring [7, 9, 12, 15, 17, 20, 21]. As the mortar ring dries, the shrinkage was prevented by the steel ring, which results in the development of restrained tensile stress in the mortar specimen. The simple ring specimen geometry allows it to be fabricated easily. In addition, the low cost of the system enables several tests to be conducted concurrently over long periods of time.

This paper utilized the restrained ring test to gather information as internal stress development in the mortar system. Figure 2 shows the ring restraint test device used in this study. The outer steel ring was used as mould during casting the DMPM specimen, and the inner steel ring was used as restraint. The inner ring was fixed on a subbase which was made of hydrophobic surface smooth material.

The internal ring strain induced by the DMPM shrinkage was measured by 4 strain gauges, axisymmetrically fixed at the midheight of the inner surface of the metal rings (Figure 2). On the other hand, in this paper, "a quarter bridge" strain gage was collected to test stress, and data acquisition automatic logging interval was set to 30 min. The constant temperature of test environment is at 20 ± 2°C, and the relative humidity is 50 ± 5 percent.

The ring specimen is shown in Figure 3. The ring was restrained against horizontal movement in the radial direction, and internal pressure, $p$, develops when the ring shrinks. Based on theory of elasticity, the stress was composited by one component $\sigma_\theta$ (in the circumferential direction) and the other component $\sigma_\mathrm{r}$ (in the radial directions). The stress $\sigma_\theta$ and $\sigma_\mathrm{r}$ can be calculated according by the following equations:

$$\sigma_\theta = \frac{(r_\mathrm{e}/r)^2 + 1}{(r_\mathrm{e}^2/r_\mathrm{i}^2) - 1} p, \tag{1}$$

$$\sigma_\mathrm{r} = \frac{(r_\mathrm{e}/r)^2 - 1}{(r_\mathrm{e}^2/r_\mathrm{i}^2) - 1} p, \tag{2}$$

$$\alpha = \frac{(r_\mathrm{e}/r)^2 + 1}{(r_\mathrm{e}^2/r_\mathrm{i}^2) - 1}, \tag{3}$$

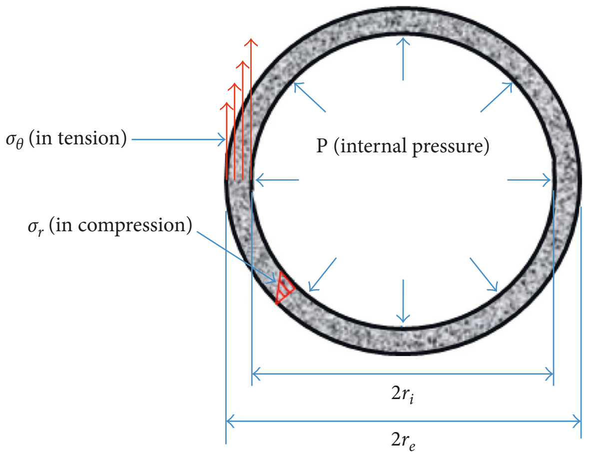


Figure 3: Distribution of internal stress and simplification for fracture analysis.

where $r_e$ and $r_i$ are the external radius and internal radius, respectively. Distributions of $\sigma_\theta$ and $\sigma_r$ are indicated in Figure 3. $\alpha$ is a constant associated with the device. $p$ is the internal pressure of the internal ring. The internal pressure, $p$, can be tested by strain gages at test points I, II, III, and IV. The value of $p$ is average measurements of these four test points. The relationship between circumferential shrinkage and the internal pressure $p$ can be obtained by elastic stress analysis.

$$p = \frac{E\varepsilon_\theta}{(r_e^2 + r_i^2)/(r_e^2 - r_i^2) + \mu},$$
$$\beta = \frac{E}{(r_e^2 + r_i^2)/(r_e^2 - r_i^2) + \mu}, \tag{4}$$

where $\varepsilon_\theta$ is the shrinkage strain, $E$ is the modulus of elasticity, and $\mu$ is Poisson's ratio, and in this paper, $\mu = 0.28$. $\beta$ is a constant associated with the device.

So, (1) can be rearranged to yield

$$\sigma_\theta = \alpha\beta\varepsilon_\theta. \tag{5}$$

In this experiment, two identical specimens were conducted. In order to reduce friction between the subbase and the specimens, two layers of plastic film were covered on the upper surface of the subbase. The DMPM mixture was casted into the mould with two layers. And the specimens were placed in standard conditions (the constant temperature of test environment was $20 \pm 2^\circ$C, and the relative humidity was $50 \pm 5\%$) until the initial drying age of 2 d, 3 d, 5 d, and 7 d. Before the dry experiment being started, the specimen surface must be covered with moist layer of linen and stamped with plastic film to prevent moisture to loss. The next step was to remove the outer ring and to seal the outside of the specimen with aluminum foil to ensure that water loses only through the outer surface of the specimen. Then, samples began to dry.

*2.4. Restrained Shrinkage Test B: Plate Test.* The method of plate test was performed following "cement mortar crack

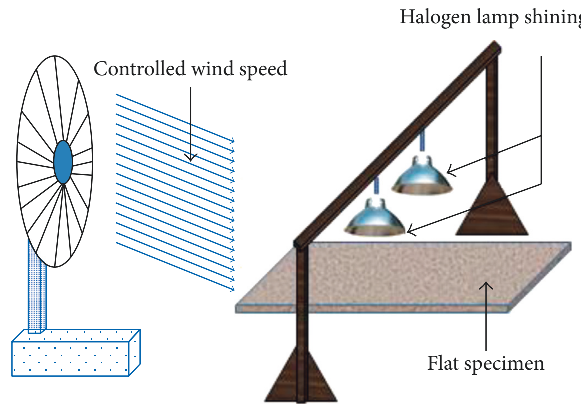


Figure 4: Schematic diagram of the plate-restrained test.

resistance test method" (Chinese technical specification JC/T 951-2005). In order to study the influence of drying conditions on cracking tendency of DMPM, the specimens were exposed to ambient condition at the age of 1 d, 2 d, 3 d, 5 d, and 7 d. During the drying period, the direction of the wind from electric fan was parallel to the surface of the plate specimen. The wind speed in the specimen transverse centerline was 0 m/s, 4 m/s, and 8 m/s. At the same time, two 1000 W power halogen lamps were lighting for 4 h. After 24 h, the width and length of crack were measured and the crack index is calculated. The schematic diagram of the plate-restrained test is shown in Figure 4.

## 3. Results and Discussion

*3.1. Influences of Initial Drying Age and Wind Speed on Flexural Strength and Compressive Strength of DMPM.* Strength (compressive strength and flexural strength) characteristics of DMPM played a decisive role in its crack resistance. After an initial moist curing period of 1 d, 2 d, 3 d, 5 d, and 7 d, the development of compressive strength and flexural strength of DMPM was performed with the age increasing.

Figures 5(a)–5(c) show that the initial drying age and wind speed would have adverse effects on the flexural strength of mortar and the same as on compressive strength. On one hand, when DMPM be exposed to drying condition earlier, more water would be evaporated from it. On the other hand, greater wind speed means faster rate of moisture evaporation. The both undermine hydration of DMPM and in turn affect the strength. The influence of DMPM's initial drying age on its strength is more mild than that of different wind speeds.

*3.2. Drying Shrinkage (DS) Characteristics of DMPM under Different Conditions.* In order to discuss water loss rate (WLR) laws and drying shrinkage characteristics of DMPM, we analyzed the relationship between water loss rules and drying shrinkage of DMPM by experiments.

*3.2.1. Influence of Wind Speed on Water Loss Rate (WLR) of DMPM.* During the drying process, the free and absorbed

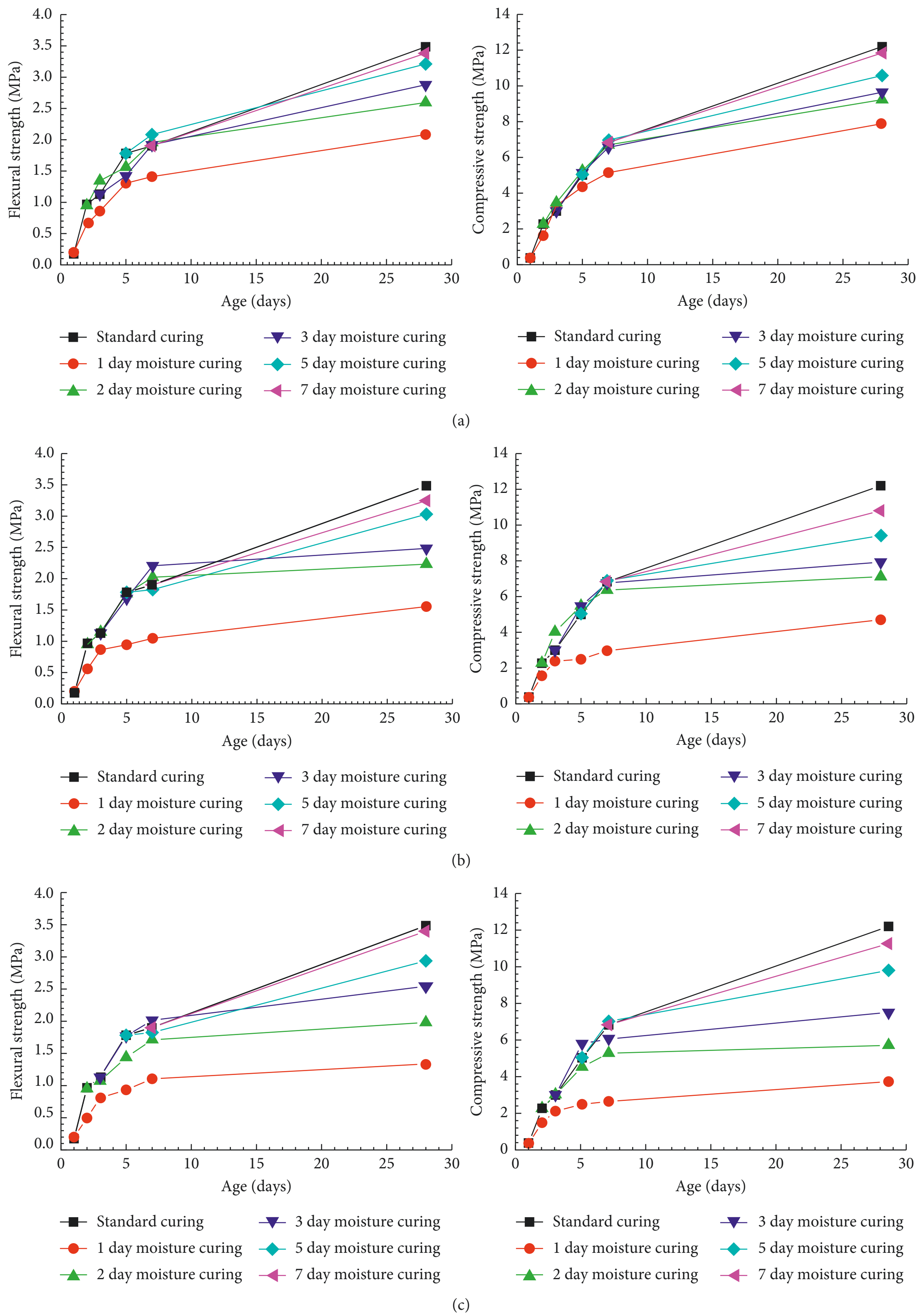


Figure 5: Flexural strength and compressive strength with different wind speeds. (a) 0 m/s. (b) 4 m/s. (c) 8 m/s.

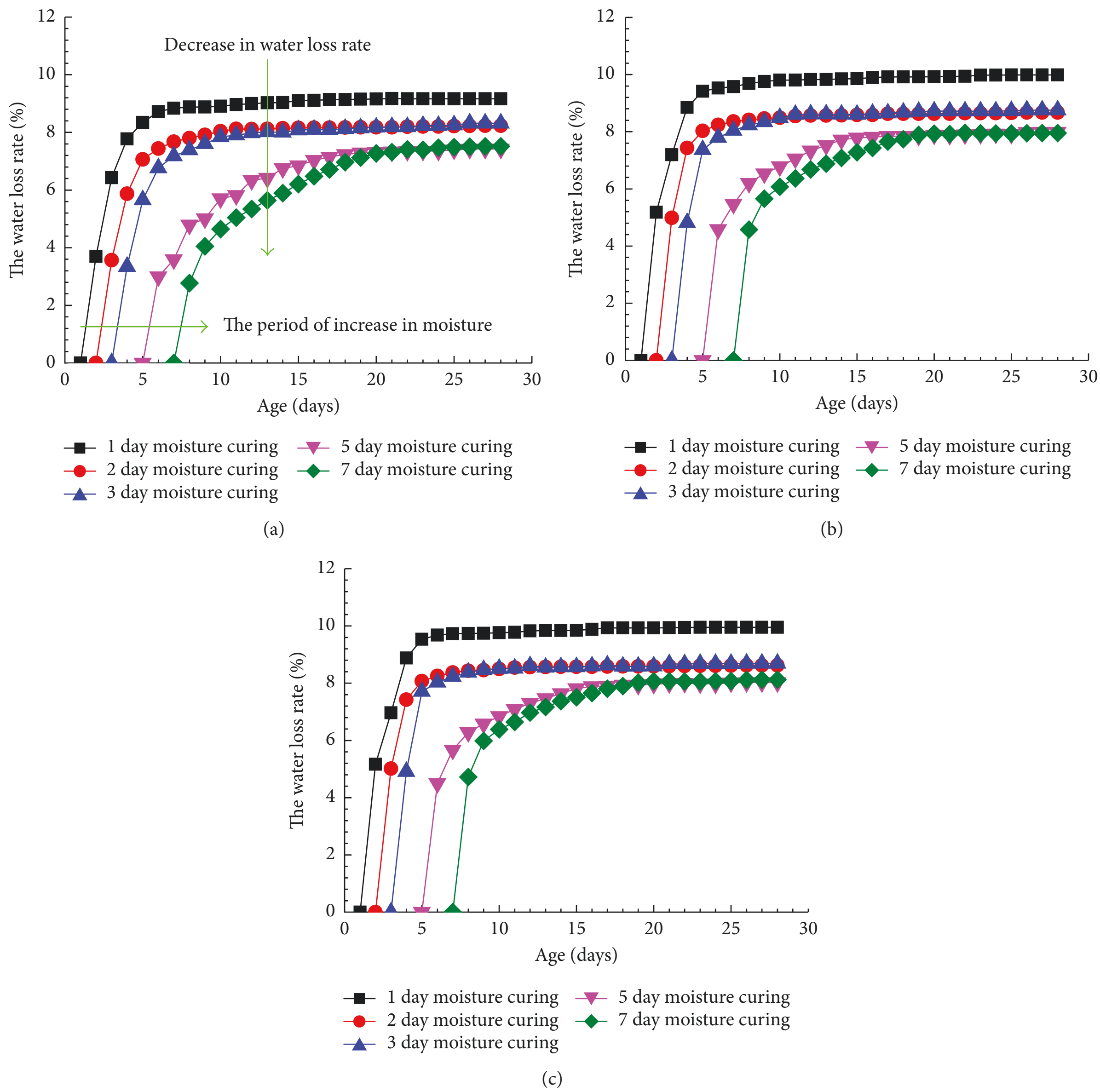


Figure 6: The water loss rate with different wind speeds. (a) 0 m/s. (b) 4 m/s. (c) 8 m/s.

water is lost from DMPM. It affects the performance of DMPM. We investigated WLR under different curing conditions, including wind conditions and initial drying age. Figures 6(a)–6(c) show the values of WLR of DMPM in different wind speeds of 0 m/s, 4 m/s, and 8 m/s. The WLR of DMPM was rapid at the early stage, but it decreased with the age, and WRL became slower gradually, until it comes to constant values.

*3.2.2. Relationships between Water Loss Rate (WLR), Initial Drying Age, Wind Conditions, and Drying Shrinkage (DS) of DMPM.* Obviously, water loss rate, initial drying age, and wind conditions affect the drying shrinkage of DMPM. The curves of Figures 7(a)–7(e) show the relations between wind speed conditions, initial drying age, and drying shrinkage. According to the ultimate shrinkage value, we can classify the rate of water loss to three grades: first, maximum WLR, for the initial drying age was 1 day; second, middle WLR, the initial drying age was 2 d and 3 d; and third, minimum WLR, the initial drying age was 5 d and 7 d. We can make different strategies to deal with the water loss of DMPM.

In the early age, drying shrinkage of DMPM increased with age, and then the development of drying shrinkage slowed down. The rate of DMPM drying shrinkage was faster at initial age and then tended to be gentle. On the other hand, in the same wind speed, the later the initial drying age, the larger the drying shrinkage value of DMPM was, which was due to much more water lose, and the volume change was larger. But the effect was remarkable at drying age from 5th day to 20th day. And it was more obvious while the wind speed was 4 m/s and 8 m/s.

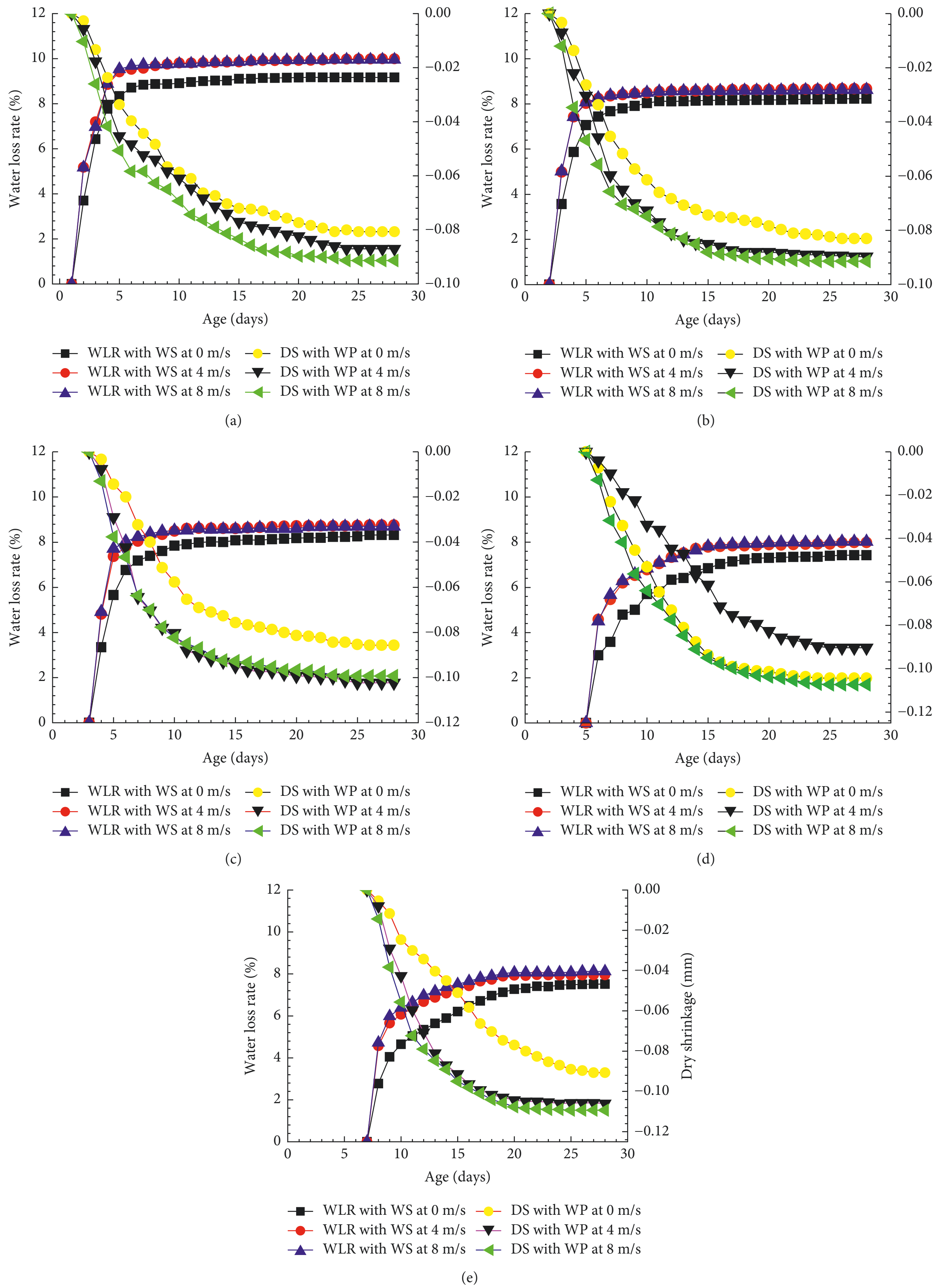


Figure 7: Water loss rate of DMPM with different moisture curing times. (a) 1 day. (b) 2 days. (c) 3 days. (d) 5 days. (e) 7 days.

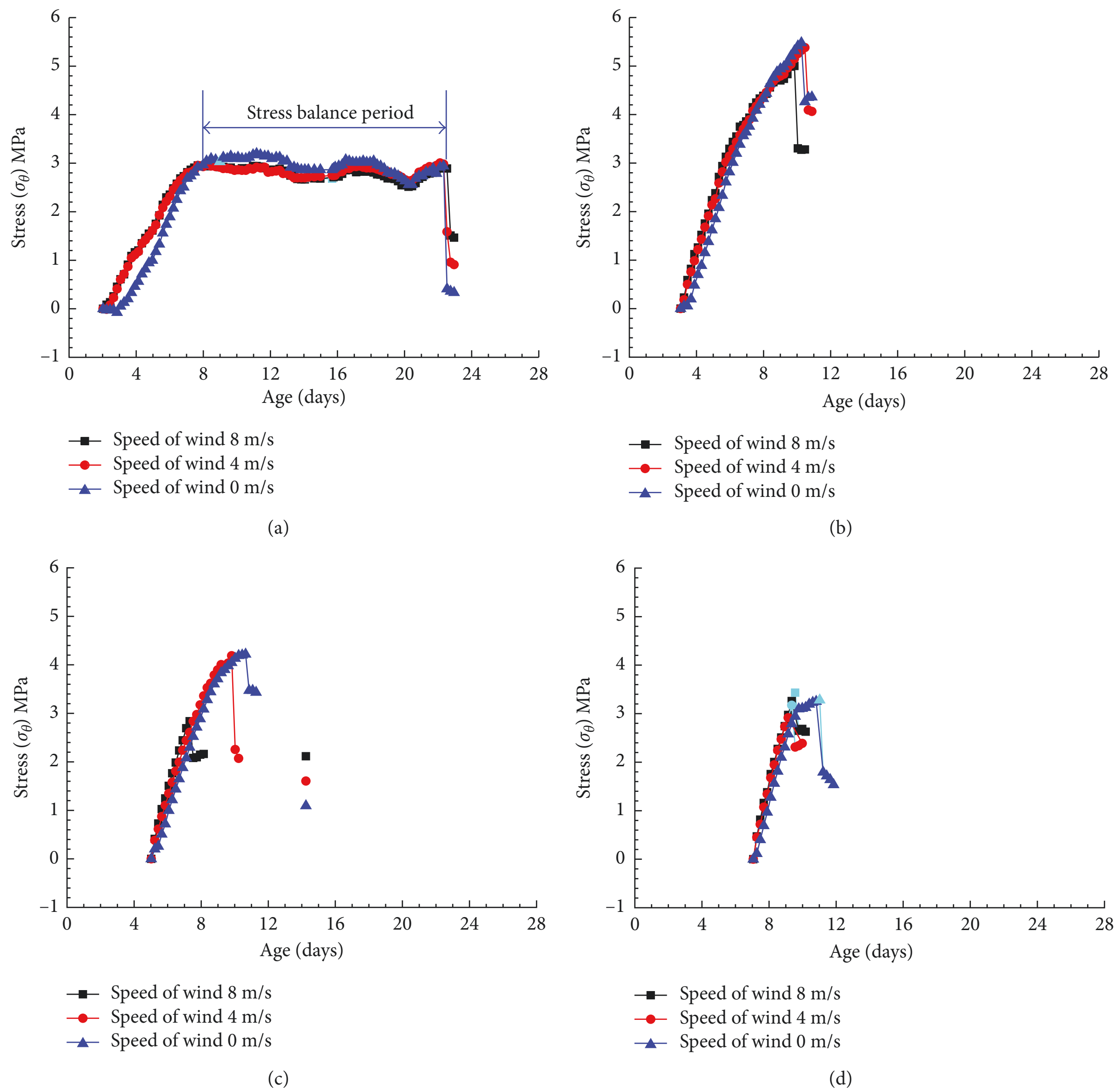


Figure 8: Shrinkage stress with different moisture curing ages. (a) 2 days. (b) 3 days. (c) 5 days. (d) 7 days.

*3.3. Cracking Tendency of Restrained Shrinkage Test: Ring Test and Plate Test*

*3.3.1. Ring Test.* Obviously, the ring test can provide quantitative information on DMPM early age stress and cracking of DMPM. The tests showed that, firstly, under the same initial drying age, the greater the wind speed, the faster the development of the DMPM ring test strain was and the greater the restraint effect of the steel ring on the DMPM ring, the larger the tensile stress induced by drying shrinkage. The reason was that the water loss occurs earlier while DMPM is exposed in the dry environment, and the elastic modulus of DMPM ring was lower. The test results also showed that the drying shrinkage value that corresponds to the cracking moment was greater as the cracking age of the DMPM ring was delayed. Conversely, if the cracking age of the DMPM ring was earlier, the cracking stress of the DMPM ring was smaller. It indicated that the DMPM drying shrinkage deformation was smaller. It means that the anticrack performance is weak. Finally, under the same wind speed, the development rate of the tensile stress was smaller while the DMPM sample was exposed to the dry environment sooner.

Figure 8(a) shows that the shrinkage stress development of the DMPM sample, which was exposed to the dry environment after 2 d moisture curing, had a stress balance period and continued for two weeks. But the phenomenon was not observed during the tests of DMPM with other initial drying age. Our interpretation of this is that, first of all, the elastic modulus of the DMPM ring specimen was smaller as the initial drying age was 2 d, and the restrained stress was smaller; secondly, the internal free water of pieces of the DMPM specimen was enough to hydrate and evaporate, and then drying shrinkage of the ring specimen

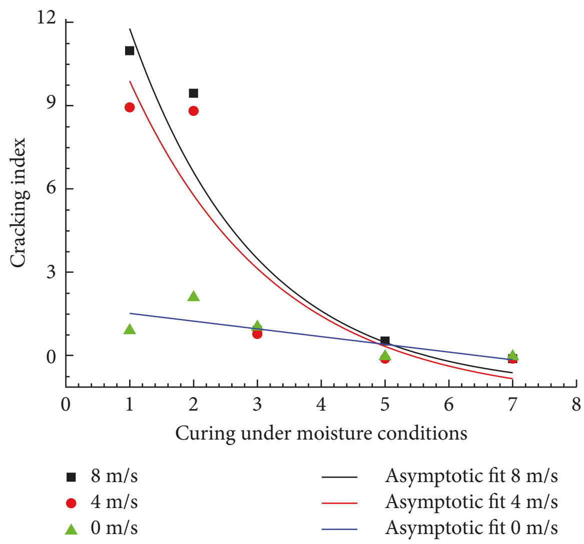


Figure 9: The relationship between cracking index and initial drying age.

increases slowly. Due to the abovementioned three reasons, a stress balance period occurs.

*3.3.2. Plate Test.* The cracking index data of flat test (Figure 9) showed that the cracking occurs more easily while the initial drying age of DMPM was earlier. More cracks would be produced when the plate sample moisture evaporated faster, and the value of cracking index test was larger as the wind speed was larger. But this phenomenon holded only for initial 3 d moisture curing. The plate specimen starts to dry after 3 d curing under moisture conditions, and the value of the crack index had a same appearance in different wind conditions. The results also showed that the cracking index presented an exponential decay with age increasing in wind environment, but appeared linear attenuation in nonwind environment.

## 4. Conclusions

The aim of this experimental work was to study the influences of environment conditions on cracking tendency of DMPM. Relevant results were obtained during the experimentation:

(1) The steel ring restrained test is an effective experiment method to measure restrained stress and strain of DMPM.

(2) The ring tests showed that under the same initial drying age of DMPM, the greater the wind speed, the faster the development of the ring test strain was, and the greater the restraint effect of the steel ring on the ring test piece, the larger the tensile stress caused by the shrinkage was. If cracking age of circular test pieces was earlier, the DMPM drying shrinkage deformation was smaller. It means that the anticrack performance is weak. Under the same wind speed, the sooner the DMPM sample exposed to the dry environment, the smaller the development rate of the tensile stress is. The development of internal shrinkage stress of DMPM, which pieces were stored in dry environment after 2 day age curing in moisture condition, possessed a stress balance period and continued for some time

(3) The flat tests showed that the cracks produced more easily while the initial drying age of DMPM was earlier. The cracking index presented an exponential decay with age increasing in wind environment, but appeared linear attenuation in nonwind environment.

In summary, in order to eliminate cracking tendency of DMPM, it should avoid water loss from the plaster layer during construction in practical engineering, especially, before initial drying ages.

## Conflicts of Interest

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

## Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (Project nos. 51378471 and 51778583). They also thank everyone for providing assistance for this study. In addition, thanks are extended to everyone for their contributions to the experimental work.

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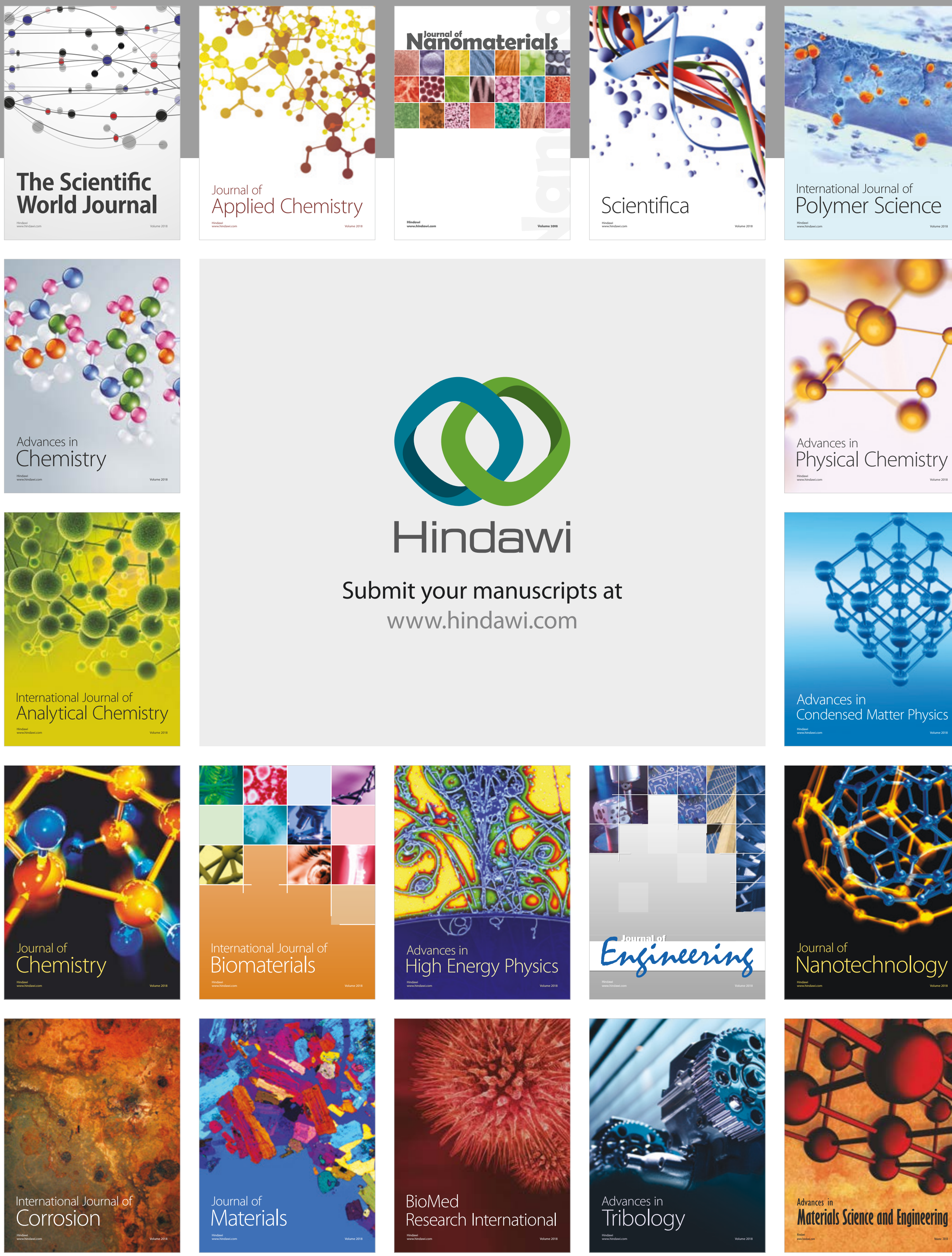
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