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Research Article

Effect of Adjusting for Particle-Size Distribution of Cement on Strength Development of Concrete

Daegeon Kim

Architecture Engineering, Dongseo University, Busan, Republic of Korea

Correspondence should be addressed to Daegeon Kim; gun43@gdsu.dongseo.ac.kr

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The massive construction projects such as nuclear power plants and gas storage plants operate their own batch plants for appropriate supply of a massive amount of ASTM Type I cement. The batch plants have difficulty responding to diversifying consumer requirements such as early strength development of concrete under the current limited production line of cement. In order to respond to the needs, this study collected several sizes of cement particles from different filters at a cement plant, and conducted the adjustment of cement particle-size distribution to enhance the properties of concrete based on ASTM Type I cement. This paper shows the chemical properties and physical tests such as setting time and compression tests considering the effects of the distribution of cement particles. Also, the classification based on cement particle-size distribution was defined as FMC (fineness modulus of cement). As FMC increased, compressive strength was relatively low at early age but the difference became smaller for later age. The test results show the effects of the adjusted mix proportion considering particle-size distribution of cement on strength development of concrete. Therefore, it is possible to see that customized cement or concrete can be manufactured in response to various consumer requirements by introducing such method that by-passes and collects fine or coarse cement in the cement-crushing process and then re-mixes them with OPC ASTM Type I cement depending on FMC.

1. Introduction

It is known that the quality and type of cement are significant factors to determine the strength development of concrete, which is specifically affected by the fineness and mineral composition of cement. The fineness of cement also affects its reactivity with water. Generally, the finer the cement, the more rapidly it will react [1, 2]. However, the cost of grinding and the heat evolved on hydration set some limits on fineness.

It is reported in the study that the rate of reactivity and the strength development can be enhanced by finer grinding of cements. It is generally agreed that cement particles larger than 45×10^{-6} m are difficult to hydrate and those larger than 75×10^{-6} m could never hydrate completely. However, an estimate of the relative rates of reactivity for similar cement composition cannot be made without knowing the complete particle-size distribution by sedimentation methods [3–5].

The concrete of early strength development attributable to more contents of fineness cement particles is used for construction sites which is sensitive to the duration and cost of construction completion. Sometimes, customers require early concrete strength of over 5 MPa in fourteen hours, even if the only production line of normal cement is available in the cement plant, or if the limited number of batch plants for normal cement in the construction sites is operated for the massive construction projects. In order to address those needs, various approaches such as the use of different types of cement and the change of distribution of cement particle sizes can be provided, which the former increases its cost. As considering economy, the cement resulted in the way of adjusting the particle-size distribution through separately collecting the fineness cement in the regular cement-grinding process of normal cement production line without additional grinding process can be equatable with the cement of ASTM Type III in terms of early strength development.

Han et al. [6] reported how the grinding process in cement plant and cement fineness affects in mortar exclusive of the effect of aggregates. According to the process of the general production line of Type I cement, which is called the normal cement, in South Korea, when a clinker and other mineral additives are provided and grinded in the cement ball mill, the grinded material is transferred to the cyclone separator. At this stage, the insufficiently grinded particles are going to be fed back and go through the regrinding process in the cement ball mill so that fine particles are sent to cement silos and made into cement mixtures. In the process of air classification, excessively grinded particles are flown into and collected in the separator bag filter along with discharged air and then are mixed with properly grinded particles together with the fine particles that have been collected in the main bag filter, and finally are inserted into the silo through the bucket elevator for the production of regular Type I cement products. Also, the research conducted several tests to evaluate the properties of cement mortar containing the finer cement particles collected from the bag filter and the coarser cement particles collected from the tube mill than Type I cement. It was reported that the effect of the fineness cement particles on the strength development of concrete was investigated. And it was concluded that the mortar including different sizes of fineness cement particles behaves close to concrete properties of ASTM Type III.

The effect of cement fineness on mortar was also investigated by Hu et al. [7]. It was reported that cement fineness and water-to-cement ratio (W/C) affected the heat of hydration and set times. The initial and final set times of coarser cement were found to be late compared to finer cement. It was concluded that the decreased surface area of coarser cement delayed the rate of hydration.

Sajedi and Razak [8] reported that the surface area of cement particles was associated with strength development and hydration. The authors showed that the rate of hydration depended on the fineness of cement particles, and high fineness was required for a rapid development of strength.

The review of the literatures indicates that the fineness of cement has been studied due to the rapid development of concrete strength. Also, it is indicated that the appropriate distribution of fine particles of cement can be contributable to the decrease of heat of hydration. But, the studies were confined to investigation of only mortar exclusive of effects of aggregates. It is thought that the limited results may be attributable to not much quantity of fineness cement collected from plant equipment. This paper focused on investigating the properties of fresh and hardened concrete based on the different contents of the very fine particles adding coarse aggregates to apply the mixed concrete to real construction in terms of strength development. The mix proportion in previous researches was newly required considering the effects of coarse aggregates in this study.

This paper aims to analyze the effect of the various classifications of particle-size distribution of cement through re-mixing to enable customized production of cement for consumers in the limited Type I cement production facilities. The main objectives of this study are thus to investigate the properties of fresh concrete including finer cement than Type I cement, to investigate the flowability and strength development of concrete with respect to the various classifications of particle-size distribution of cement, and to develop the relationship of compressive strength using the various classifications of particle-size distribution of cement and concrete ages.

2. Experimental Plan and Approach

2.1. Material. Chemical composition of the material used in this study is shown in Table 1. Table 1 shows that the ignition loss (LOI) of fineness cement (FC) is high comparing to ASTM Type I cement (OPC) and coarse cement (CC). Cement with a density of 3.15 g/cm^3 was used in this study, and the Blaine fineness for FC, OPC, and CC is given in Table 2. River sand and crushed sand were mixed in a proportion of 50 : 50 for fine aggregates, whereas coarse aggregates were a mixture of 5 to 10 mm and 10 to 25 mm aggregates in a proportion of 35 : 65. Other physical properties of aggregates are shown in Table 3. And the properties of admixtures are shown in Table 4.

2.2. Approach. To evaluate the effect of the classifications of particle-size distribution of cement, the mix proportion was newly required. Nine mix proportions by the amount of different sizes of cement were classified based on the accumulated remains denoted as R at 10 μm (R10), 20 μm (R20), 40 μm (R40), and 80 μm (R80) using an Alpine air jet sieve shaker, as shown in Table 5, and the fineness modulus (FMC) of the distributed cement particle sizes as integers shown in (1) was used. Generally, a lower value of FMC has the effect of reducing the size of cement particles which is advantageous to the increase of initial strength, and on the contrary, as the higher value of FMC increases the size of cement particles, it is more favorable in the reduction of hydration heat.

$$\text{FMC} = \frac{(\text{R80} + \text{R40} + \text{R20} + \text{R10})}{100}. \quad (1)$$

The experimental variable related to the change of FMC is finest cement (FMC: 0.50), which are particles excessively grinded during the production process of Type I cement (OPC) that have flown into and collected in the separator bag filter together with discharged air, and relatively coarse cement (FMC: 1.69) primarily grinded in the tube mill were input proportionally to substitute Type I cement (OPC) of FMC with 1.11 for manufacturing. Table 6 shows the results of fineness distribution using the sieves of 1 μm, 24 μm, 64 μm, and 200 μm.

2.3. Experimental Plan. The scope of tests on the properties of concrete using fineness cement consisted of the fundamental tests with fresh concrete, slump, air contents, and setting time [9–11]. The experiment was planned with the following targets; slump of 120 mm ± 25 mm, water-to-cement ratio of 0.5, and air content of 4.5% ± 1.5%. As for experimental items, unit volume mass [12] and setting time were measured for fresh concrete, and compressive strength [13] of up to 91 days of age was to be measured for hardened concrete. The density of all the types of cement was planned to be 3.15.

The mixture proportion for the experiment was designed by FMC with nine levels through proportional substitution of fineness cement shown in Table 1. Data on the concrete mix fixed at this stage is shown in Table 7.

Table 1: Chemical composition of cement.

Name	Chemical element (%)								LSF	SM	IM
	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O			
FC	0.54	21.24	5.01	3.68	62.91	2.00	3.17	1.31	89.55	2.44	1.36
FO1	0.50	21.40	5.01	3.68	63.23	2.01	2.84	1.22	89.78	2.46	1.37
FO2	0.45	21.56	5.02	3.67	63.55	2.01	2.50	1.12	90.00	2.48	1.37
FO3	0.40	21.72	5.02	3.67	63.87	2.01	2.17	1.02	90.22	2.50	1.37
OPC	0.35	21.88	5.02	3.66	64.18	2.01	1.83	0.92	90.44	2.52	1.37
CO1	0.31	21.96	5.06	3.70	64.25	2.02	1.66	0.91	90.34	2.51	1.37
CO2	0.27	22.03	5.10	3.74	64.31	2.03	1.49	0.90	90.24	2.50	1.36
CO3	0.23	22.11	5.14	3.78	64.38	2.04	1.32	0.89	90.14	2.49	1.36
CC	0.18	22.18	5.17	3.82	64.44	2.05	1.14	0.87	90.03	2.47	1.35

LSF, lime saturation factor; SM, silica modulus; IM, iron modulus. FO1, FO2, and FO3 consist of the mixture of FC and OPC by the different value of FMC. CO1, CO2, and CO3 consist of the mixture of CC and OPC by the different value of FMC.

Table 2: Blaine fineness of cement (cm^2/g).

FC	FO1	FO2	FO3	OPC	CO1	CO2	CO3	CC
6,479	5,752	5,024	4,174	3,324	2,920	2,515	2,164	1,813

Table 3: Physical properties of aggregate.

Classification	Density (g/cm^3)	Fineness modulus	Absorption rate (%)	Amount of pass through 0.08 mm strainer (%)
Fine aggregate	2.59	2.67	1.11	1.12
Coarse aggregate	2.71	7.01	1.18	0.11

Table 4: Physical properties of admixture.

Classification	Form	Property	Color	pH	Density (g/cm^3)
SP agent	Liquid	Polycarbonate	Ivory white	6.5	1.06
AE agent	Liquid	Negative ion	Ivory white	—	1.04

SP, superplasticizer; AE agent, air-entrained agent.

3. Experiment Results and Analysis

3.1. Fresh Concrete. Figure 1 shows the fine aggregate ratio as well as the unit water contents according to the change of FMC. As FMC increased, fine aggregate ratio had to be gradually decreased to secure target fluidity, and unit water content had to be first decreased and then increased centering on OPC of which FMC is 1.11. This is considered to be related with the ratio increase of 200 μm size of which the particle diameter is relatively big as can be seen in Table 6.

Figure 2 illustrates the usage amount of SP and AE agents following the change of FMC. The usage amount of the SP agent had to be reduced, whereas the usage amount of the AE agent did not have any special effect. As FMC increases, the size of cement particles increases, which leads to smaller surface area that can contact water and lower viscosity. To secure viscosity, the unit volume had to be increased with regard to unit cement volume, and as FMC increased by 0.1, the average diameter of cement grew by approximately 1.7 μm, which eventually is the effect of increased fluidity due to the decrease in the number of cement particles, having to reduce the usage amount of the SP agent.

Figure 3 and Table 8 demonstrate penetration resistance according to progressed time by FMC. As FMC increased, the setting time was delayed in proportion, which is considered to be a result of delayed hydration due to smaller surface that can contact water as there is more distribution of coarse particles as FMC increased. As FMC increased by 0.1, the final set was delayed by about 0.42 hours. But, slump results did not show any tendency for the various FMC values.

3.2. Hardened Concrete. Table 9 shows the experiment results of relationship between compressive strength and FMC according to age, respectively. Figure 4 shows the compressive strength ratio of concrete mix proportions comparing to Type I cement according to concrete age. The ratio of 100% in Figure 5 means the compressive strength of Type I cement mix proportion at 91 days.

At this point, as FMC increased, compressive strength dropped, and there was a big difference of compressive strength in the initial age; however, the difference in compressive strength became smaller in the latter age. As a result, strength revelation grew at a wider span with the progress of age as FMC increased, which can be analyzed as a consequence of continuous hydration of unhydrated cement with the progress of age, whereas hydration happens slowly at initial age due to small surface area that can contact water because of the low fineness of high FMC.

For the estimation of compressive strength, the OriginPro 7.5 [14] program was used to set the cement fineness modulus and age as the independent variable and compressive strength as the dependent variable, to calculate parameters such as slope and intercept by conducting multiple regression analysis.

$$f_{cu} = 11.177 \times \log D - 11.364 \times \text{FMC} + 25.146, \quad (2)$$

Table 5: FMC based on (1).

Name	Type	Residue (%)				FMC
		At 80 μm (R80)	At 40 μm (R40)	At 20 μm (R20)	At 10 μm (R10)	
FC	FC	0.6	4.0	14.5	30.6	0.50
FO1	FC + OPC	0.9	5.7	20.0	38.2	0.65
FO2	FC + OPC	1.2	7.5	25.5	45.8	0.80
FO3	FC + OPC	1.6	9.2	30.9	53.8	0.95
OPC	OPC	1.9	10.9	36.4	61.8	1.11
CO1	CC + OPC	3.0	15.8	41.8	64.9	1.25
CO2	CC + OPC	4.0	20.6	47.1	67.9	1.40
CO3	CC + OPC	5.1	25.1	52.8	71.4	1.54
CC	CC	6.1	29.6	58.4	74.8	1.69

Table 6: Fineness distribution of cement.

FMC	Fineness distribution (%)				Average particle diameter (μm)	Remains of 200 μm (%)
	Pass of 1 μm	Pass of 24 μm	Pass of 64 μm	Remains of 64 μm		
FC	16.1	73.8	8.9	1.2	5.1	0.0
FC1	13.8	71.7	12.7	1.8	7.4	0.0
FC2	11.4	69.5	16.5	2.5	9.7	0.0
FC3	9.0	67.5	20.4	3.1	12.0	0.0
OPC	6.6	65.4	24.2	3.8	14.1	0.0
CO1	6.2	60.0	27.9	5.9	16.5	0.0
CO2	5.9	54.5	31.6	8.1	19.8	1.4
CO3	4.9	48.9	36.0	10.2	22.4	3.8
CC	4.0	43.3	40.4	12.3	24.9	6.1

Table 7: Mixture proportion.

Name	S/a (%)	W (kg/m^3)	SP/C (%)	AE/C (%)	Unit volume (kg/m^3)				
					FC	C	CC	S	G
FC	48	183	0.71	0.017	366	—	—	315	341
FO1	47	182	0.66	0.018	91	274	—	309	348
FO2	47	181	0.61	0.018	180	180	—	310	349
FO3	46	180	0.53	0.018	91	271	—	304	357
OPC	46	178	0.51	0.018	—	356	—	305	359
CO1	46	178	0.51	0.020	—	268	88	305	359
CO2	46	180	0.49	0.019	—	180	180	304	357
CO3	46	185	0.48	0.019	—	91	277	300	352
CC	46	195	0.45	0.019	—	—	391	293	343

S/a, sand-coarse aggregate ratio; W, mixed water; S, sand; C, cement; G, aggregate.

where f_{cu} is compressive strength (MPa); FMC is the fineness modulus of cement; and D is the age based on log scale, day.

The result of (2) indicated that compressive strength declined as FMC increased and increased as age progressed. Compressive strength could be estimated and the estimation acquired through this study showed a good correlation with 0.942 of coefficient of determination. Figure 5 shows the comparison between the compressive strength estimated through (2) and the actually measured compressive strength by using the scatter plot. The correlation coefficient turned out to be 0.942, which can be interpreted that there is a decent level of estimation accuracy between the estimated and actually measured compressive strength.

4. Conclusion

This study reviewed the effects of the change of FMC on the mixing and strength revelation properties to analyze the manufacturing possibility of customized cement following the change of the FMC, which expresses particle-size distribution of cement as integers, and the results are summarized as follows:

(i) Regarding the mixing properties of fresh concrete, since the average particle diameter of cement grows as the FMC increases to maintain the same level of slump and air content which leads to lower viscosity, S/a and unit quantity had to be reduced until FMC 1.11, which then had to be increased afterwards and the usage amount of the SP agent had to be reduced to secure viscosity.

(ii) Setting time was delayed proportionally due to low fineness as FMC increased, which was a delay of about 0.42 hours per 0.1 increase of FMC.

(iii) The estimation formula for compressive strength using FMC and ages was derived through the

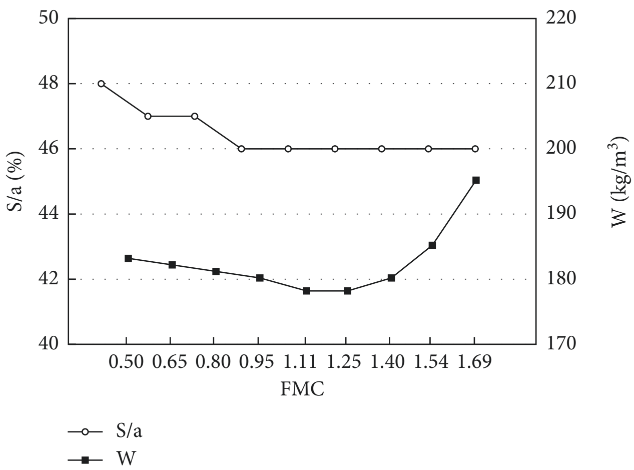

Figure 1: Fine aggregate ratio and water contents in accordance with FMC change.

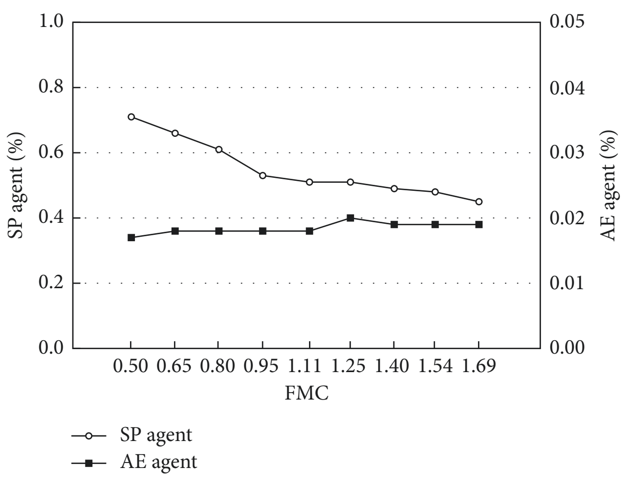

Figure 2: Amount of chemical admixture in accordance with FMC change.

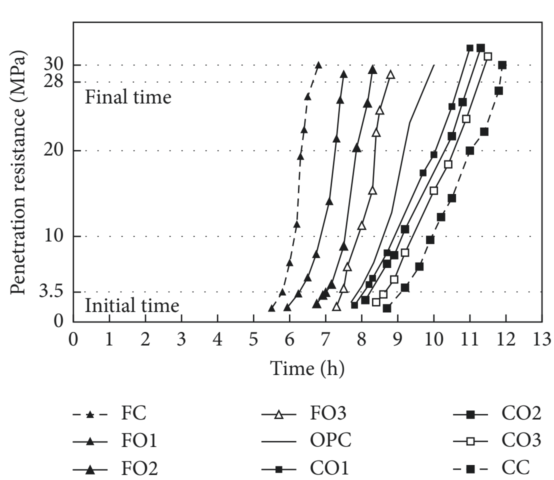

Figure 3: Penetration resistance.

Table 8: Results of fresh concrete test.

Name	Slump (mm)	Slump flow (mm)	Air content (%)	Setting time (hr)	
				Initial	Final
FC	125	235	5.6	5.8	6.6
FO1	137	225	4.1	6.3	7.4
FO2	130	234	4.9	6.9	8.3
FO3	119	222	5.2	7.4	8.6
OPC	122	220	5.1	7.9	9.7
CO1	134	235	5.1	8.1	10.8
CO2	110	220	3.9	8.3	11.1
CO3	116	227	3.3	8.7	11.3
CC	130	231	4.4	8.9	11.8

Table 9: Result of the compression test (unit: MPa).

Name	1 day	3 days	7 days	28 days	91 days
FC	19.7	25.9	30.6	35.3	38.9
FO1	17.6	24.5	29.8	32.9	35.7
FO2	13.2	22.9	28.3	31.6	34.6
FO3	12.2	22.4	27.8	30.4	33.7
OPC	9.1	20.6	26.0	29.5	33.1
CO1	6.8	18.2	22.7	28.4	32.6
CO2	5.3	14.8	21.7	26.3	30.5
CO3	4.1	14.0	17.9	24.6	29.0
CC	3.0	11.0	17.0	22.7	28.4

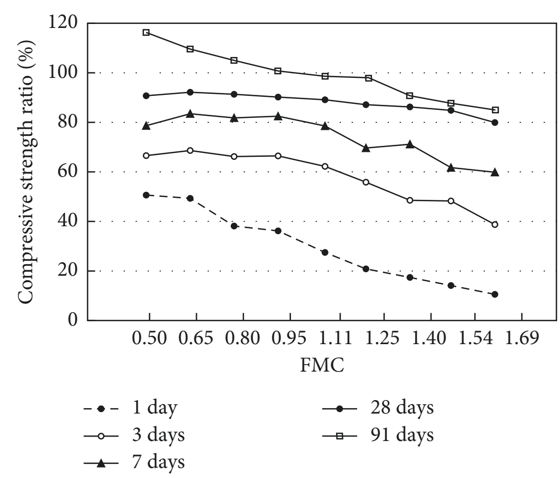

Figure 4: Compressive strength ratio against FMC values.

multiple regression analysis, and as a result of comparing the estimated and actually measured compressive strength, there was a high correlation with a correlation efficient of 0.942, demonstrating decent estimation accuracy.

(iv) It is concluded that customized cement or concrete that meet the diverse needs of the consumers can be manufactured when fine or assembled cement are by-passed, collected in the cement-grinding process, and then re-mixed with ASTM Type I cement according to FMC. Lower value of FMC has the effect of reducing the size of cement particles, which is

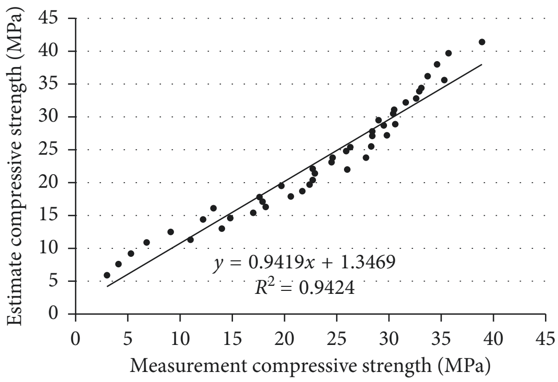

Figure 5: Comparison of estimated compressive strength by formula and measured compressive strength.

advantageous to the increase of initial strength. For construction in cold region, this customized cement by the change of FMC may contribute to improving quality of concrete due to early development of strength without costly action using ASTM Type III.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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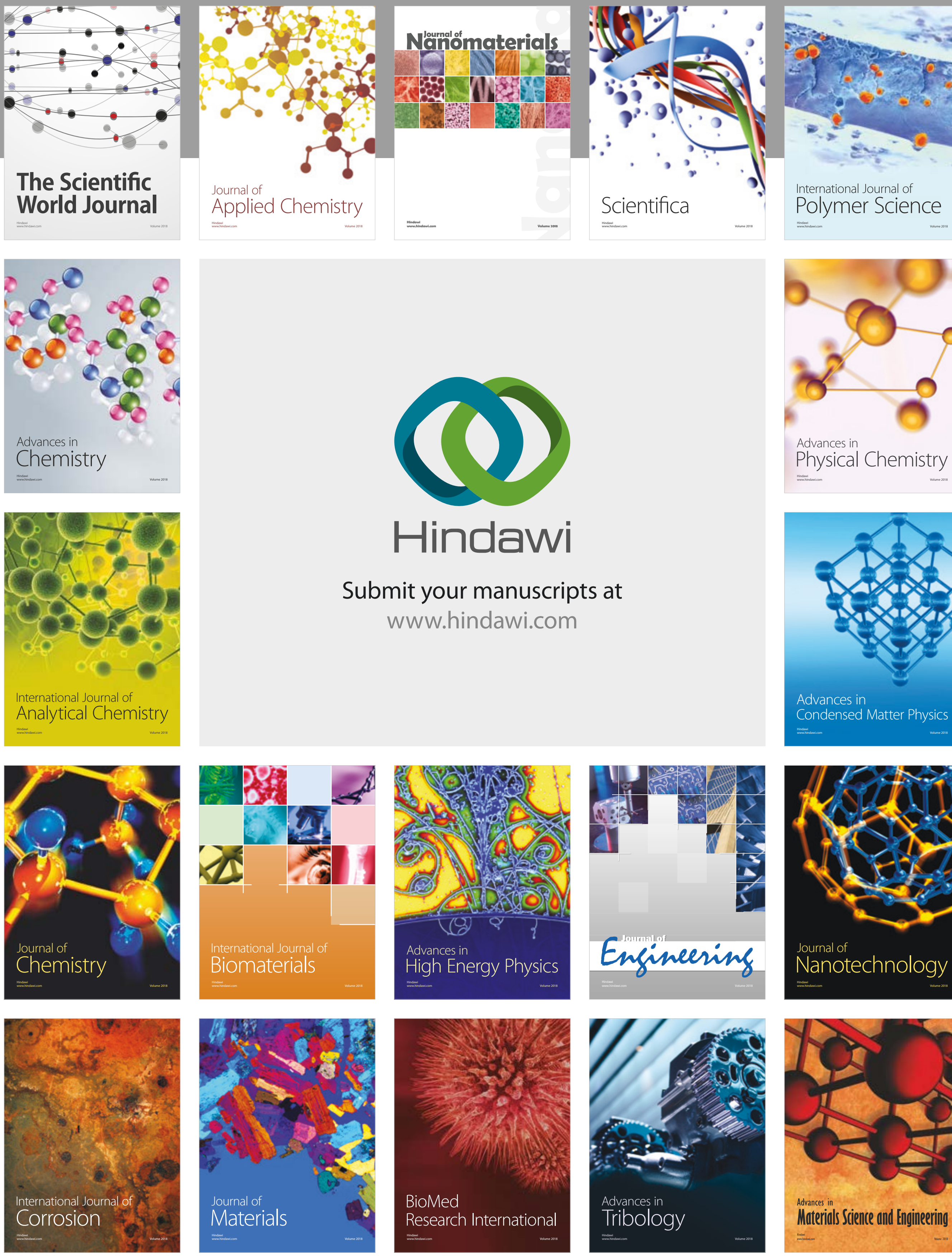

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