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Research Article

Cement-Based Renders Manufactured with Phase-Change Materials: Applications and Feasibility

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The paper focuses on the evaluation of the rheological and mechanical performances of cement-based renders manufactured with phase-change materials (PCM) in form of microencapsulated paraffin for innovative and ecofriendly residential buildings. Specifically, cement-based renders were manufactured by incorporating different amount of paraffin microcapsules—ranging from 5% to 20% by weight with respect to binder. Specific mass, entrained or entrapped air, and setting time were evaluated on fresh mortars. Compressive strength was measured over time to evaluate the effect of the PCM addition on the hydration kinetics of cement. Drying shrinkage was also evaluated. Experimental results confirmed that the compressive strength decreases as the amount of PCM increases. Furthermore, the higher the PCM content, the higher the drying shrinkage. The results confirm the possibility of manufacturing cement-based renders containing up to 20% by weight of PCM microcapsules with respect to binder.

1. Introduction

With the dawn of twenty-first century, the sustainable development in terms of economic, social, and environmental fields is gaining more and more importance. Sustainability in the construction industry [1] can be achieved through three different main routes based on the abatement of atmospheric emissions [2–4] and reuse or recycling of natural resources [5–8] and the reduction of raw materials quarrying [9–13]. Heating and cooling of buildings and domestic hot water production require about 40% of energy consumption of the whole European community. In the Mediterranean area, Italy is the country with the highest energy consumption for residential buildings since the majority of the existing buildings were built in the second half of the last century, neglecting energy saving strategies. As a result, a typical Italian house has an average energy consumption of $140 \div 170\ \mathrm{kWh/m^2 \cdot year}$ for heating purposes [14] and also the summer cooling plays an important role in terms of energy consumption. Furthermore, the energy used for houses mainly comes from fossil fuels, whose consumption is increasing and it is becoming environmentally unsustainable. In a real estate market characterized by growing demand for high quality buildings, living comfort is becoming a key factor. Acoustic, temperature, humidity and, in general, living comfort together with a better air quality are necessary to improve the Indoor Environmental Quality (IEQ).

The heating energy produced during the winter and cooling energy produced during the summer tend to naturally flow towards the environment. In order to reduce temperature fluctuations, such flux has to be reduced to improve thermal comfort. Dispersion to the outside can be reduced by improving the building envelope, for example, by using materials characterized by low thermal conductivity. This is the main strategy for the maintenance of the thermal conditions inside the building. In recent years, the increasing requirements in terms of life quality and living comfort have modified the function of the building envelope, achieving more complex features. As an example, the increasing use of underfloor heating systems in combination with suitable building envelope thermal insulation ensures itself homogeneous distribution of the heat in the house at low temperatures of heating fluids.

The achievement of building energy efficiency is also possible thanks to the use of thermal energy storage techniques. The contribution of these technologies is reflected both directly, through the extensive use of the thermal energy supplied by solar radiation, and indirectly, by improving the heating and cooling systems operating strategies. The thermal energy storage (TES) systems provide efficiency not only in those areas characterized by particularly cold climates, but also in temperate zones. They permit to "store" a certain quantity of energy to be used in subsequent periods, after the accumulation phase. This translates into the ability of the building enclosure to counteract the heat flux, contributing to the reduction of thermal fluctuations. The TES systems store energy during the accumulation period (charge) and then release it later through the phase transition. The most important characteristics of a storage system are essentially the duration, that is, the time during which the energy can be stored efficiently, the accumulation density, that is, the amount of energy stored in the unit of volume (measured in kWh/m^3), and the efficiency, given by the ratio between the energy extracted during discharge and the energy stored during the charge. The thermal storage systems can be classified as SHTES (Sensible Heat Thermal Energy Storage) if the heat is stored into material during temperature fluctuations and LHTES (Latent Heat Thermal Energy Storage) if the heat is stored in almost isothermal conditions, during phase transition. The LHTES offers a series of advantages, as a reduced temperature difference between the accumulation and release cycles. These systems are based on the use of phase-change materials (PCM), which are materials able to absorb and release energy during the phase transition. Among all the thermal energy storage methodologies, LHTES obtained by using phase-change materials is the best energy storage system because it allows considerable improvements in terms of energy efficiency [15–19]. PCM for thermal regulation of buildings can be integrated into lime, gypsum, cement, or other raw materials through direct mixing or impregnation. Over the past forty years, many materials have been studied to assess the performances of several types of PCM. The substances were mainly hydrated salts, paraffinic waxes, fatty acids, organic and inorganic polymers, and eutectic compounds [20–22]. Paraffin is the most promising phase-change material due to high latent heat, low cost, low vapour pressure, good thermal and chemical stability, and nontoxicity. However, paraffin suffers subcooling and liquid loss during the solid-liquid phase transition. Such issues can limit their use in several applications. PCM can be subdivided into three main groups, depending on the temperature at which the transition occurs. There are low temperature thermal storage systems characterized by phase transition temperatures lower than 15°C, intermediate temperature systems working between 15–90°C, and high temperature systems above 90°C. PCM can also be classified according to the phase transition: gas-liquid, solid-gas, solid-liquid, and solid-solid. In the building industry, PCMs with solid-liquid phase transition are of great interest, since they allow to store considerable amounts of energy in the range of temperatures between 15 and 40°C. In the light of this consideration, paraffin is the most promising solid-liquid phase-change material available nowadays. In addition, the average length of the hydrocarbon chain may be modified to adjust both the temperature and the heat of fusion. The commercial paraffin waxes and other pure paraffin exhibit stable properties and good thermal reliability even after thousand cycles [23, 24].

Phase-change materials are generally enclosed in capsules to be embedded in structural elements and to avoid the dispersion into the cement matrix. The shell of the capsule should resist physical actions resulting from collisions with aggregates, shear stresses during the mixing procedure, and chemical actions promoted by the alkaline environment of a traditional cement-based material. In addition, it should be thermally efficient and have a high specific surface area to increase the thermal energy transfer efficiency. For this purpose, the microencapsulation technique meets all these requirements and the microencapsulated phase-change materials MEPCM have attracted considerable attention for more than twenty years. The microencapsulation technology is widely used in several industrial sectors, that is, textiles, adhesives, cosmetics, medicines, and other medical applications. The MEPCM are also used in solar energy installations and advanced building materials.

However, the use of microencapsulated PCM in various applications for heat control is limited due to increasing costs. In addition, the shell-like structure of the MEPCM reduces the natural convection and increases the rate of heat transfer, further reducing the thermal storage per unit of volume. To overcome this, the PCM can be macroencapsulated in high volume containers—up to several litres—to be put inside special features in the structural elements.

PCMs were taken into account for the thermal storage in buildings since 1980. The TES systems can be applied to buildings to attain two different aims: the exploitation of the heat of the sun or the cold night air and the efficient conversion of artificially produced energy. There are different types of passive systems, which are characterized by achieved energy gain. PCMs may be conveniently inserted in the perimeter walls or in other components of the buildings to ensure a progressive release of heat when the internal or external temperature reaches the melting point of the material. Nowadays, the most important phase-change material for these applications exhibits a melting temperature between 22 and 25°C, which is the interval of heating and cooling of zero-energy buildings. Among the many applications that involve the inclusion of PCM for building elements, we can cite the Trombe walls, laminate coatings, light walls for prefabricated structures, blinds and shutters, bricks, floor heating systems, ceiling panels, and others. The possibility of using these materials in such a high number of applications emphasizes the need to develop high performance PCMs and define suitable design rules for practical applications. In addition, evaluation procedures are needed to assess the benefits deriving from the application of such technologies.

In recent years, many researches dealing with the application of PCMs in cementitious or gypsum-based plasters have been performed [25–32]. Authors confirmed the need

Table 1: Mix design.

Type	CEM I 42.5R	Hydrated lime	Water	Aggregates	PCM
RM	240 g	80 g	275 g	1680 g	
PCM 5	240 g	80 g	375 g	1680 g	100 g
PCM 5*	300 g	80 g	340 g	1620 g	100 g
PCM 10	300 g	80 g	430 g	1620 g	200 g
PCM 10*	360 g	80 g	400 g	1560 g	200 g
PCM 20	360 g	80 g	580 g	1560 g	400 g
PCM 20*	420 g	80 g	580 g	1500 g	400 g

to increase the dosage of PCM up to 50% by mass to achieve benefits in terms of energy storage. The studies show that the PCM addition results in an slight increase of the specific heat and decrease in thermal conductivity of the materials, but significant increase in the thermal inertia was found. Researches also highlight that the performances are not linearly related to the PCM dosage. The heat storage capacity increases with the amount of microcapsules and the incorporation of paraffin well increases the total heat stored by the mixture. The thermal energy stored by the plaster at the maximum dosage of MEPCM is more than two and a half times compared to reference. Finally, it was observed that the latent heat significantly increases with the amount of microcapsules and paraffin content. Plasters seem to be the more promising application of PCM for the building industry, although it is necessary to investigate more in depth the effects of the addition of PCM on the rheological, mechanical, and physical properties of the material.

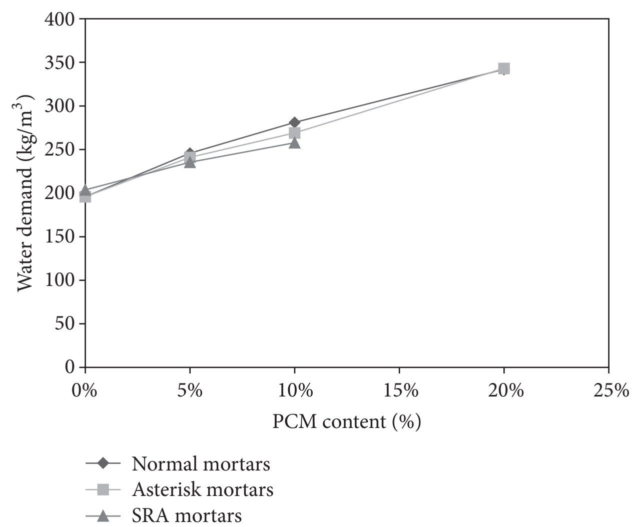


Figure 1: Water demand as a function of PCM content.

2. Experimental

Ten renders were manufactured (Table 1) by changing microencapsulated PCM content, binder/PCM ratios, and admixtures. Renders were manufactured with cement CEM I 42.5 R, hydrated lime, natural siliceous aggregates with 2.5 mm maximum diameter, and air-entraining agent at a dosage of 0.1% by solids mass. Mixtures were designed by considering the same amount of dry solids (cement, lime, and aggregates), equal to 2000 g. Methylcellulose was added in order to improve the thixotropy and plasticity. Shrinkage reducing admixture based on ethylene glycols was also used [33]. Commercial microencapsulated PCMs (n-heptadecane) with characteristic diameter of 5 μm, thickness of the shell of PMMA microcapsule equal to 0.1–0.2 μm, and melting temperature equal to 23°C were used. The microencapsulated PCMs were added at percentages of 5%, 10%, and 20% by solids mass. Several mixtures were manufactured: in the first series—named normal mortars—only the cement content was varied and such variation implies the reduction of aggregates content to achieve the same amount of dry solids. The second series—identified by the asterisk—was manufactured with a higher binder content, a lower water/binder ratio, and a different content of aggregates in order to achieve compressive strength at least equal to the reference render without microcapsules. The water dosage was adjusted in order to achieve a constant workability at the end of the mixing procedure, equal to 150 mm spreading. Rheological and mechanical tests were performed. The shrinkage was measured both on prismatic specimens (40 × 40 × 160 mm) according to UNI EN 12617-4 and by means of devices able to measure the real-time deformation of the mixture in plastic and hardened conditions by means of electronic calipers.

3. Results and Discussion

The experimental data confirm a higher water demand by increasing PCM dosage, up to 75% for the render with the maximum dosage of microcapsules (Figure 1). The effect is mainly ascribable to the higher specific surface of the microparticles and is directly connected to the need to increase the volume of cement paste as the amount of microcapsules increases. As a consequence of this, it is necessary to increase the amount of binder to attain the target workability at the same water/binder ratio, since the use of plasticizers or superplasticizers technologically would affect the thixotropy of the mixture. The increase of the PCM dosage causes a decrease in the compressive strength. Data collected at 28 days (Figure 2) showed

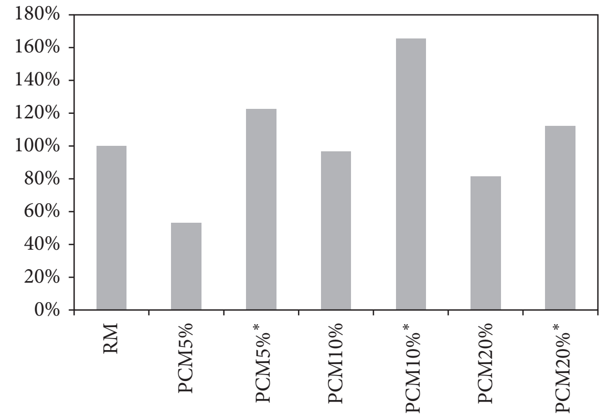


Figure 2: Compressive strength of mortars (data normalized with respect to reference mortar RM).

a marked decrease related to PCM addition. An increase of the binder content at the same w/c ratio permit itself to partially mitigate such behaviour, meaning that the cement paste amount is a key factor affecting the ability to embed microcapsules and limit clustering effect. A further reduction of the water/binder ratio coupled with an increase with the binder content permits to achieve higher compressive strength values compared to reference RM, meaning that an improvement of the quality of cement paste permits to mitigate the negative effect of microcapsules addition on the compressive strength. At the maximum dosage of microcapsules—equal to 20% by mass—the content of cement was increased by 50% to achieve rheological and mechanical properties comparable to the reference render RM. The shrinkage is also significantly affected by the addition of microcapsules. The higher the amount of PCMs, the higher the shrinkage. High shrinkage values are mainly due to the higher volume of cement paste, the lower dosage of aggregates, and the increasing amount of PCM, which are characterized by low stiffness due to their chemical nature. However, this effect can be mitigated by the addition of SRA with a significant decrease in shrinkage just after 7 days (Figure 3). Morphological characterization of the fracture surfaces of specimens was carried out after compressive strength tests. The images collected by means of scanning electron microscope on specimens manufactured with the higher amount of microcapsules showed the presence of embedded, unbroken capsules, and damaged microcapsule shells (Figure 4). The microcapsule distribution is quite uniform and only the presence of few microcapsule clusters was noticed. However, the rupture of several shells has to be further investigated to determine the causes, most probably related to the mechanical action of the high speed mixing device.

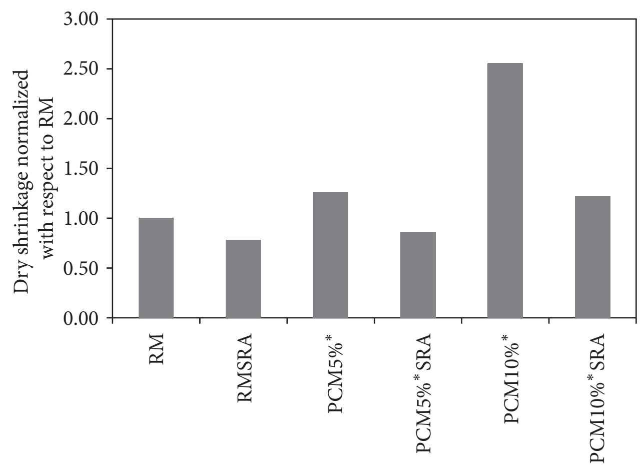
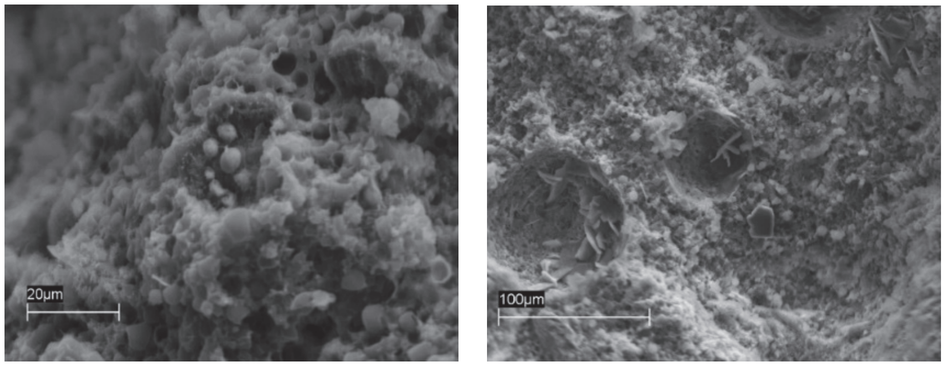


Figure 3: Dry shrinkage of mortars normalized with respect to reference mortar RM.

4. Conclusions

The paper is devoted to the study of the mechanical and rheological behaviours of cement-based renders manufactured with PCM to improve energy saving and living comfort of buildings. Specifically, it moves from the literature analysis of the most suitable application of PCM in the building industry to address their application in cement-based renders. Nowadays, several systems with PCM are investigated and it is therefore necessary to outline the areas of use of such products in order to maximize and optimize their performances. The results confirm that the production of cement-based renders with PCM up to 20% by mass is technologically feasible. The experimental data confirm a higher water demand by increasing PCM dosage. The effect is mainly ascribable to the higher specific surface of the microparticles. The increase of the PCM dosage causes a decrease in the compressive strength at 28 days. The effect can be only mitigated by increasing the binder content and by decreasing the water/binder ratio. The increase of the amount of PCMs causes an increases in the shrinkage, which can be reduced only by the addition of SRA. A more in-depth assessment of the effect of microcapsules damage is further needed.



(a) (b)

Figure 4: Image at SEM of the mortar with 30% PCM by binder mass (a) and details of cement matrix with high dosage of microcapsules (b).

Competing Interests

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

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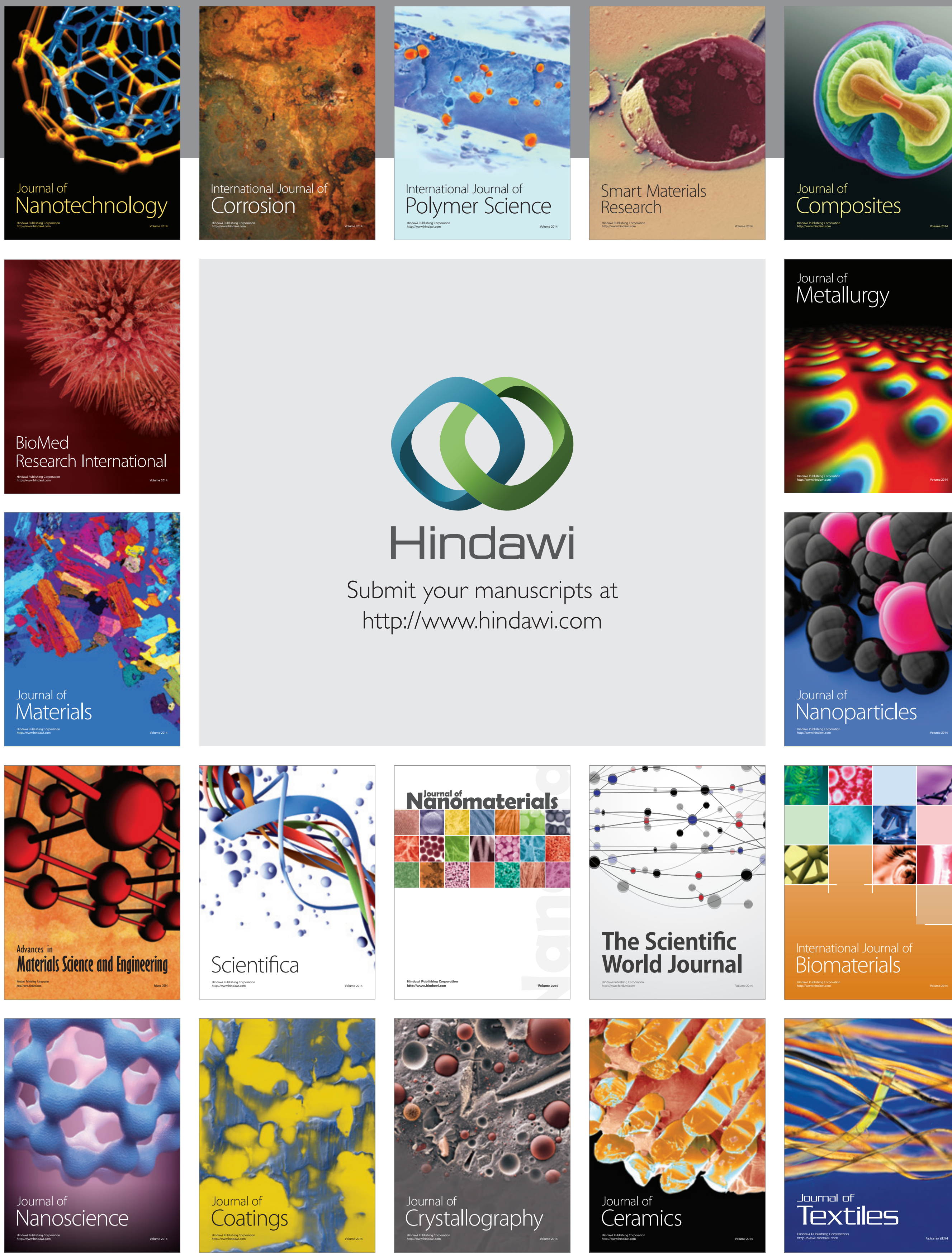
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