Investigation of Compatibility of Fluorine-Acrylic Emulsion and Sulphoaluminate Cement in the Design of Composite Coating: Effects of Sorbitol and Its Mechanism

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Abstract

Both fluorine-acrylic (FA) emulsion and sulphoaluminate cement (CSA) have been proved as satisfactory marine engineering materials, and a better performance can be expected by their combined use. However, their compatibility has rarely been researched. In this study, the effects of sorbitol and its mechanism are investigated by the cement paste fluidity, rheological property, tensile strength, water absorption and scanning electron microscopy (SEM) tests. The results showed that, compared with sodium tripolyphosphate, borax and sodium gluconate, sorbitol can significantly improve the double electric layer of FA, and the absolute value of Zeta potential was increased by 25% compared with the blank sample without any retarder added. With the increase of sorbitol dosage, the fluidity, rheological behavior, tensile strength and water absorption sharply changed first and then tended to be stable after sorbitol dosage reached the optimal dosage of 0.25% for the compatibility improvement. The morphology analysis also proved its advantages, but the more significant improvement can be ensured by a larger polymer to cement ratio (p/c) value. Finally, the mechanism hypothesis is proposed. The film formation rate of the emulsion matches the hydration rate of the cement, due to sorbitol addition.

Keywords: Polymer-modified cement-based coating; Compatibility; Retarders; Rheological properties.

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1. Introduction

In recent decades, anti-corrosive coatings have been developed rapidly.^[1,2] Traditional organic coatings, having poor weather resistance, are easy aging under ultraviolet radiation and easily cause some pollution to the environment. Cement, as a rigid waterproof material, has good durability and poor flexibility. As a composite material of organic-inorganic, the most important feature of polymer-modified cement-based coatings is its designability of properties and structures.^[3]

Organic fluorine-modified acrylate emulsion has become the representative of high weatherability acrylate coatings in recent years.^[4,5] Because F-C bond energy is 486

kJ/mol, much higher than that of C-C (351 kJ/mol), its molecular structure is more stable. The fluorine atom is not only strongly bonded with the carbon atoms on the main chain, but also closely arranged in the outer layer of the carbon skeleton, which effectively protects the main chain.^[6] The addition of organic fluorine can maintain good film-forming property of acrylate emulsion, and it also has the characteristics of water resistance, heat resistance and ultraviolet resistance.^[7] In the meanwhile, compared with ordinary Portland cement, sulphoaluminate cement (CSA) has the characteristics of rapid hydration and hardening, satisfactory anti-corrosive properties and excellent volume stability, which makes it widely used in various ocean engineering fields.^[8-10] Thus, the composites between them are expected as a powerful combination. But they are not a simple physical blending, which is restricted by the compatibility of polymer emulsion and cement hydration products.^[11] The essence of compatibility is the interaction in the process of polymer film-forming and cement hydration. The influence of polymer on cement hydration is

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that polymer can be adsorbed on the surface of cement particles, which inhibits cement hydration and affects the construction of early inorganic network.^[12,13] Actually, the influence of cement hydration, detailed as the increase of pH value, Ca^{2+} concentration and water loss, on polymer film formation is more significant.^[14,15] Take Ca^{2+} for example, Ca^{2+} can destroy the stability of emulsion under the action of high valence electrons, resulting in the agglomeration of particles and destruction of emulsion.^[16]

Interestingly, compatibility between polymer emulsion and CSA has received only limited attention in literatures and most results are concluded in the view of polymer modification.^[17-19] For example, Yilmaz *et al.*^[20] researched the preparation of a tert-Butyl acrylate/Butyl acrylate/methacrylic acid ternary copolymer/clay nanocomposite containing 3 wt% sodium montmorillonite via seeded emulsion polymerization, finding that a certain amount of emulsifier was necessary to obtain stable latexes and the usage of a low molecular weight water soluble polymer as steric barrier increased the stability of system. Zhao *et al.*^[21] prepared the Ca^{2+} ion responsive Pickering emulsions based on the properties of poly sodium salt nanoaggregates and indicated that the adsorption of poly sodium salt nanoaggregates at the interface is the key to the stability of the emulsions. Ishikawa *et al.*^[22] found that the steric interaction produced by the surfactant likely resulted in the stable dispersion of this latex.

Here, we focus on the modification of cement and expect to find an effective retarder for CSA,^[23-25] which can match the FA film formation process through the hydration rate control, and has no significant harm to the performance of the polymer. In addition, the effect of the above suitable retarder on the composite coating is investigated by the analysis of cement paste fluidity, rheological property, tensile property, water absorption and microstructures. Finally, the mechanism is also proposed.

2. Experimental

2.1 Materials

One of the main materials used in this study is fluorine-containing acrylic ester copolymer emulsion (FA). Originally, three commercially available FAs with over 10% of fluorine contents are selected and labeled as E1, E2 and E3, respectively. The basic properties of FAs are shown in Table 1 (MFT refers to the minimum film forming temperature). Their Fourier-transform infrared (FTIR) spectra are given in Fig. 1, showing a similar group composition. The effective grafting of fluorine monomers is characterized by C-F stretching vibration at 1100 and 670 cm^{-1} , respectively. The stability of Ca^{2+} in emulsion is an important index for reflecting the initial compatibility between polymer emulsion and cement. Fig. 2 presents the values of critical coagulation concentration (CCC) and the residual ratio on sieve (RRS). E1 shows the highest CCC value and lowest RRS value, indicating the most satisfactory

stability for Ca^{2+} among the above FAs. In the following work, E1 was selected as the target FA raw materials. The sulphoaluminate cement (type 42.5), abbreviated as CSA, used in this research was from China United Cement Corporation, China. The chemical composition of CSA, obtained from XRF analysis, is shown in Table 2.

Table 1. Properties of the FAs.

No.	pH	Solid content/%	Viscosity/mPa.S	Particle size/ μm	MFT/ $^{\circ}\text{C}$
E1	7.6	48	560	0.1-2	30
E2	8.6	45	630	0.1-5	30
E3	7.9	45	470	0.1-2	28

Fig. 1 The FTIR spectrum of FAs

Table 2. Chemical composition of CSA (%)

Composition	CaO	Al ₂ O ₃	SO ₃	SiO ₂	MgO	Fe ₂ O ₃	TiO ₂	K ₂ O	Others	LOI
Content (%)	45.26	21.39	15.38	9.52	2.39	2.51	0.70	0.41	0.83	1.61

Fig. 2 The Ca^{2+} stability of FAs.

Borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$, CHN), sodium gluconate (SG, $\text{C}_6\text{H}_{11}\text{NaO}_7$, CHN), sorbitol ($\text{C}_6\text{H}_{14}\text{O}_6$, CHN) and sodium tripolyphosphate (STPP, $\text{Na}_5\text{P}_3\text{O}_{10}$, CHN) are compared to obtain the best retarder for improving compatibility. Some

admixtures such as the dispersant (sodium hexametaphosphate), film-forming additive (Texanol) and antifoaming agent (Foamastar MO 2190AC) were also used in this study.

2.2 Sample preparation

The process flow diagram of coating preparation is shown in Fig. 3. Firstly, the emulsion was stirred at 300 rpm for 1 min to disperse the emulsion particles evenly. Retarder and dispersant (0.3% by mass of FA) were slowly added and continuously stirred at the speed of 600 rpm for 3 min, and then film-forming additive and antifoaming agent were added in amounts about 3% and 0.5% based on the weight of FA to complete the basic preparation of liquid materials in coatings. Secondly, pre-weighted cement was added to the liquid materials and rapidly mixed at the speed of 600 rpm for 5 min to ensure uniform distribution. Finally, the obtained slurry was rested for 2 min for defoaming and then poured into the mould ($350 \times 320 \times 1.5 \text{ mm}^3$) for coating preparation. In this research, the curing regime of coatings was adopted, which was cured for 96 h under $25 \pm 2^\circ\text{C}$ and a relative humidity of $70 \pm 10\%$. Subsequently, after demoulding, the coating was dried in the oven at $45 \pm 2^\circ\text{C}$ for 48 h. The relevant experiments were carried out at room temperature for at least 24 h.

2.3 Methods

2.3.1 Critical coagulation concentration (CCC)

The CCC value test was performed according to the Chinese standard 'GB/T 20623-2006'. It started with 5wt% of CaCl_2 solution and the weight percentage was gradually increased in steps of 0.5wt%. The CCC value was recorded when the emulsion started appearing flocculation.

2.3.2 Residual ratio on sieve (RRS)

The residual ratio on sieve (RRS) was determined by the following steps. Firstly, the FA and CSA were mixed for a uniform state with the polymer-cement ratio of 0.1 (the solid

mass of the emulsion to the cement quality) and water to cement ratio of 1.0. Then the 120-mesh sieve was used to separate the coarse particles. Following that separation, RRS value was calculated. Notably, the sieve used before coarse particle separation and weight measurement had to be dried to constant.

2.3.3 Zeta potential

Zeta potential values of emulsion were determined using the Zetasizer Nano ZSP of Malvern Panalytical. Based on this test, the polymer-cement ratio and the dosage of retarder were set as 0.1 and 0.45%, respectively.

2.3.4 Cement paste fluidity

The fluidity of CSA paste ($w/c=0.35$) was evaluated according to Chinese standard 'GB/T 8077-2012'. The dosage of retarder varied from 0.05 to 0.45 wt% with a gradient of 0.1 wt%. The test time was fixed at 5 and 15 min, respectively.

2.3.5 Rheological property

The rheology test program is shown in Fig. 4. Firstly, the coating slurry was stirred at 100 s^{-1} for 30 s in order to make the coating slurry disperse evenly. Thereafter, the flow field was stabilized by stationary 20 s. Finally, the shear rate increased from 0 to 150 s^{-1} in 1 min and decreased from 150 to 0 s^{-1} , likewise in 1 min. The yield stress and plastic viscosity were fitted by the data of the falling stage.

2.3.6 Tensile property test

The dumbbell-shaped samples were used to determine tensile strength according to Chinese standard 'GB/T 16777-2008' (tensile speed is 200 mm/min). The samples were measured using the universal testing machine (CMT5504).

2.3.7 Water absorption

The samples were cut into a certain shape ($40 \times 40 \times 1.5 \text{ mm}^3$)

Fig. 3 The flow chart of the process of the polymer cement-based coating.

after curing for 7 d. Then the samples were completely immersed in water for 72 h. The weight of the sample before and after immersion was used to calculate the water absorption.

Fig. 4 The test program of rheology

2.3.8 FTIR

The FTIR spectrum of emulsion was determined using Thermo Nicolet (Nexus 870). The emulsion was put into a drying oven at 105 °C for 2 d until constant weight to build a film for FTIR analysis.

2.3.9 Scanning electron microscopy (SEM)

The field emission scanning electron microscope (QUANTA 250 FEG) was used to observe the microstructure of the fresh section of coatings (spraying time is 30 s).

3. Results and discussions

3.1 The selection of retarder

Previous studies have ever reported that some cement retarders can play a role in improving the compatibility between polymer and cementitious materials.^[11,18] Generally, the retarders used for CSA are hydroxyl carboxylate, inorganic phosphate, polyol and borate. But it is still unclear whether they all show the positive effect on the stability of emulsion, which is an important factor for the compatibility.^[26] The thickness of the electric double layer of the emulsion determines its ability to resist the damage of Ca^{2+} , thus affecting the compatibility with cement. Hence, the above retarders are firstly compared and investigated by the Zeta potential test. As shown in Fig. 5, the Zeta potential value of blank sample was reported as -2.52 mV. Most retarders, such as sodium tripolyphosphate, borax and sodium gluconate, do not show a satisfactory compatibility and reduce the Zeta potential values instead. However, the sorbitol achieves a better compatibility and increases the Zeta potential value by 25% compared with the blank sample. The added sorbitol is easy to form hydrogen bond with water molecules through hydroxyl groups, and the hydrogen bonds between water molecules form a stable water film on the surface of the emulsion particles to

prevent particle contact.^[27] It is equivalent to increasing the thickness of the electric double layer.

Fig. 5 The effect of different retarders on Zeta potential of FA.

3.2 Fluidity and rheological behavior

Fig. 6 depicts the fluidity of CSA in 5 and 15 min with various dosages of sorbitol, respectively. Both curves show a similar gradually growing tendency. However, the loss of fluidity between 5 and 15 min tends to be stable after the sorbitol is added more than 0.25%. It means that 0.25% of sorbitol is large enough for improving the fluidity of CSA. It is easy for understanding that the improvement is attributed to the retarder effect of sorbitol. Therefore, the hydration process can be retarded and the steric hindrance between cement particles can be reduced so as to improve the mutual fluidity of cement particles.

Fig. 6 The effect of sorbitol dosage on the fluidity of CSA

Although the sorbitol can increase the Zeta potential value of FA and reduce the fluidity loss of CSA, its effect on the FA-CSA composite system is worth further investigation. Rheology is the science of micro-fluidity of matter,^[28-30] which can reflect particle flow state and

microstructure development of polymer-modified cement-based coating. Based on the analysis of stress-rate curves (Fig. 7). The shear stress shows a similar trend between up curves and down curves in both samples with a polymer to cement ratio (p/c) of 0.5 and 1. The shear stress has an obvious decrease with the increase of sorbitol. But the decreased degree in all samples tends to be stable when the dosage of sorbitol is added to 0.25%. In comparison with p/c values, the global shear stress is significantly decreased when the p/c is changed from 0.5 to 1. It is well understood that the larger p/c value will cause the relative motion of interior particles more readily.

As a kind of cement paste, polymer-modified cement-based coating belongs to a non-Newtonian fluid.^[31] When the shear rate increases, obvious shear thinning occurs in the coating system. Fig. 8 shows that the apparent viscosity decreases with the increase of shear rate but tends to stabilize gradually. When the p/c value is 0.5, it is worth noting that the apparent viscosity decreases with the increase of sorbitol dosage at the same shear rate, and the shear thinning behaviour becomes more obvious. Similarly, the phenomenon can also be seen when the p/c value is 1. However, when the sorbitol dosage reaches 0.25%, the

decreasing trend of apparent viscosity is no longer obvious no matter the p/c value is 0.5 or 1. It's just that the latter has a smaller change in apparent viscosity.

The yield stress (the intercept) and plastic viscosity (the slope) obtained from the linear fitting curve are based on Bingham model. The detailed Figure description has been placed in the supporting information. The purpose of selecting the smooth stage in the curve is to eliminate the instability of the slurry caused by the low shear rate.^[31] The higher R^2 value indicates a satisfactory correlation between the experimental and the fitted values. The summary of the yield stress and plastic viscosity with different sorbitol dosages (0~0.45%) is depicted in Fig. 9. Both yield stress (Fig. 9(a)) and plastic viscosity (Fig. 9(b)) show a gradual downward trend with the increase of sorbitol dosage. However, similar to the above analysis of the fluidity, shear stress and apparent viscosity, the sorbitol dosage of 0.25% is a critical point, which separates these curves into two parts with relatively large and low slopes, respectively. It can be proved once again that the sorbitol dosage of 0.25% is optimal and large enough for compatibility improvement. The reason for the positive effect of the sorbitol is that a possible sorbitol film on cement particles strongly retards

Fig. 7 Shear stress-shear rate curves with different sorbitol dosages at a p/c value of (a) 0.5 and (b) 1.

the cement hydration. Ultimately, as the internal friction (yield stress) between particles is decreased, the viscosity of the coating system is also decreased. In addition, when the p/c value changes from 0.5 to 1, the effect of sorbitol on the yield stress and plastic viscosity seems less significant. In comparison with the sorbitol dosage of 0.25% and the reference, the yield stress and plastic viscosity are decreased by 63% and 53%, respectively. Meanwhile, they show 48% and 22% descend when the p/c value is 1. The more polymer in the mixture will lead to the less destructive effect of

cement hydration to polymer film structure.^[14] Furthermore, the polymer can give the inherent cement retarded effect. A higher polymer dosage give a higher degree of encapsulation.

3.3 Physical appearance and microstructure

Based on the above analysis, we may safely draw the conclusion that sorbitol has a positive effect on improving the compatibility of coatings. However, it is still unclear about its effect on the mechanical properties. Before that, the physical appearance is observed in advance. Fig. 10 shows the

Fig. 8 Apparent viscosity-shear rate curves with different sorbitol dosage at p/c value of 0.5 (a) and 1 (b).

Fig. 9 The yield stress and plastic viscosity with different sorbitol dosage

Fig. 10 The film formation at a p/c value of 0.5 and the dosage of sorbitol is (a) 0, (b) 0.25%, (c) 0.45%; and the film formation at a p/c value of 1 and the dosage of sorbitol is (d) 0, (e) 0.25%, and (f) 0.45%.

composite coating at a p/c value of 0.5 and 1, respectively. The obvious crack happens even with sorbitol addition when the p/c value is 0.5 ((a) (b) (c)). But it becomes much better when the p/c value reaches 1 ((d) (e) (f)). It is easy for understanding that a high p/c value is beneficial for the formation of integrated polymer film. However, it cannot be denied that the sorbitol also plays an important role in improving the microstructure of the composite coating. This can be identified by the comparison between Figs. 10(d) and (e). Thus, it follows that compatibility improvement by sorbitol is significantly positive to the properties of the composite coating, provided that a large enough p/c value is ensured.

To further identify the morphology, SEM analysis was carried out on the above coatings (Fig. 11). As demonstrated in Fig. 11(a) and Fig. 11(d), considerable cracks and voids can be recognized from samples without sorbitol. There is no or very little complete film structure and the particles are loosely packed. It indicates that the compound products cannot form a complete space film or network penetrating throughout the whole coating. This phenomenon was also reported elsewhere and explained as circumstance changing of film formation. Specifically, the rapidly released Ca^{2+} , increased pH value and water loss due to cement hydration will disturb the uniform dispersion of polymer particles which affect the early coalescence of polymer particles.^[32] While in other Figs. (b), (c), (e) and (f), where the samples are modified by sorbitol, cement hydrates can be covered by a complete and continuous film. Hence, it can be concluded that the improvement agents like sorbitol play a quite important role in the FA-CSA composite coating to avoid the appearance of scattered polymer films. The reasons for such positive effect of sorbitol will be discussed further in the mechanism analysis. Of course, the integrity of

polymer networks is also closely related to polymer content. Here, when the p/c value is 0.5 and even with the maximum dosage of sorbitol (0.45%), bare cement particles can still be seen in the coating (c). In such a condition of a low p/c value, cement hydrates will be broken through the envelopment of the polymer. As a result, the emulsion could not form a continuous membrane structure. In contrast, when the p/c value is 1.0, the ideal polymer film covers uniformly throughout the cement hydrates. It predicts that better properties will be achieved.

3.4 Tensile property

Fig. 12 shows that the tensile properties of coatings with different sorbitol dosages at a p/c value of 1. The tensile strength increases first and then tends to be stable with the increase of sorbitol dosage. It is exactly due to the complete film contributed by sorbitol. Ohama *et al.*^[33,34] have pointed out that a complete polymer network or a continuous polymer film is the key point for effective modification and properties improvement of the polymer cement composite materials. When the sorbitol is added by 0.25%, the tensile strength almost seems to be the best as 2.38 MPa, which is generally consistent with the results obtained from the rheological test mentioned above. When the dosage of sorbitol is 0.45%, it only increases by 4%.

3.5 Water absorption

Fig. 13 shows the water absorption of coatings with different sorbitol dosages. It sharply increases first and keeps a slow growth after the sorbitol dosage reaches 0.25%. This can be attributed to the fact that the polymer contains many hydrophilic groups, which will easily swell in water.^[35] As discussed above, the sorbitol can significantly improve

Fig. 11 The microstructure of coatings at p/c value of 0.5 which the dosage of sorbitol is 0 (a), 0.25% (b), 0.45% (c) and the microstructure of coatings at p/c value of 1 which the dosage of sorbitol is 0 (d), 0.25% (e), 0.45% (f)

Fig. 12 The tensile properties of coatings with different sorbitol dosage at p/c value of 1

the compound microstructure of polymer and cement. This can be ensured by uniform distribution of polymer and cement particles rather than the cluster situation. Both complete polymer networks and uniformly distributed cement particles result in a slightly higher water absorptions.^[36] For the relatively smooth stage, as the sorbitol with a higher dosage cannot further improve polymer networks and particle distribution, the water absorption tends to be stable. The dosage of sorbitol, also characterized as a hydrophilic material, may be another reason for this increase in water absorption.

3.6 Mechanism

In view of the above experimental data analysis, the compatibility between FA and CSA can be significantly

Fig. 13 The water absorption of coatings with different sorbitol dosages at a p/c value of 1.

improved by sorbitol. Here, a mechanism is proposed. At the beginning stage, FA particles and CSA are mixed together. Based on Ohama model,^[32] it can be assumed that no chemical and physical reactions happen at this stage. Then, CSA hydration starts and a large number of Ca^{2+} are rapidly released (Fig. 14(a)). FA particles have a strong tendency to link with Ca^{2+} , leading to a polymer flocculation. Also, Ca^{2+} can enter the stern layer of emulsion particles and reduce their potential energy barrier, leading to the coagulation of emulsion particles. In summary, Ca^{2+} may disturb the uniform distribution of polymer particles and break the ordered pack situation of continuous film formation. However, when sorbitol is doped (Fig. 14(b)), it is adsorbed on the surface of FA particles and cement particles due to the physical or weak chemical adsorption of electrostatic force, hydrogen bonds,

Fig. 14 The mechanism of sorbitol improving compatibility.

chelation and so on caused by the polar group (hydroxyl).^[37,38] In addition, it may be preferentially absorbed on the surface of cement particles due to the positive electricity of aluminium phase mineral in CSA and many defects on its surface [39-41]. The polarity of hydrophilic groups of sorbitol is strong enough to absorb a stable solvated water film, which can cover the surface of both FA and cement particles (Fig. 14(c)). Hence, the steric hindrance between cement particles and FA particles is reduced, which improves the rheological behaviour as discussed. Similarly, it can also slow the release of Ca^{2+} and inhibit the early aggregation of polymer particles. This is reflected in the increase of cement fluidity and the increase of Zeta potential of emulsion, respectively. In conclusion, sorbitol can really make the cement and emulsion slow-acting to form the structure of emulsion encapsulated cement, which improves the compatibility between organic and inorganic parts in the coating system.

4. Conclusions

The main conclusions drawn from the present study are:

(1) The sorbitol achieves a better stability of the organic fluorine modified acrylate emulsion than the sodium tripolyphosphate, borax and sodium gluconate. Modified by sorbitol, the Zeta potential value of emulsion is increased by 25% compared with the blank sample. The other retarders reduce the Zeta potential values instead.

(2) The sorbitol has a significantly positive effect on the fluidity and rheological behavior of the polymer-cement composite coating and the dosage of 0.25% is optimal and large enough for compatibility improvement.

(3) The sorbitol can improve the microstructure, provided that a large enough p/c value is ensured. The obvious crack happens even with the addition of sorbitol when the p/c value is 0.5. But it becomes much better when the p/c value reaches 1.

(4) With the increase of sorbitol dosage, both the tensile strength and the water absorption are increased with a similar trend, i.e., a sharp increase at first and slow growth after the sorbitol dosage reaches 0.25%. In comparison with the initial sample, the tensile strength and the water absorption are increase by 24% and 40%, respectively.

(5) The mechanism that sorbitol improves the compatibility of coatings is proposed. The addition of sorbitol makes the surface of cement particles and emulsion particles covered with a layer of water film through physical or chemical adsorption, thus matching the hydration rate of cement with the film forming rate of emulsion.

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Supporting information

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Conflict of interest

There are no conflicts to declare.

Reference

- [1] D. Balgude, K. Konge and A. Sabnis, *J. Sol-Gel Sci. Technol.*, 2014, **69**(1), 155-165, doi: 10.1007/s10971-013-3198-z.
- [2] C. Chang and J. Yeh, *Adv. Mater. Res.*, 2013, **747**, 35-38, doi: 10.4028/www.scientific.net/AMR.747.35.
- [3] H. Ma, Y. Tian and Z. Li, *J. Mater. Civil Eng.*, 2011, **23**, 1412-1421, doi: 10.1061/(ASCE)MT.1943-5533.0000302.
- [4] K. Kang, C. Kan, Y. Du and D. Liu, *Eur. Polym. J.*, 2005, **41**, 439-445, doi: 10.1016/j.eurpolymj.2004.10.032.
- [5] L. Zang, J. Guo, J. Luo and H. Zhang, *Polym. Adv. Technol.*, 2012, **23**, 15-20, doi: 10.1002/pat.1819.
- [6] M. Burnett and W. Zisman, *J. Phys. Chem.*, 1962, **66**, 1207-1208, doi: 10.1021/j100812a518.
- [7] W. Yang, Y. Chen, X. Wang, D. Han and L. Zhu, *Adv. Mater. Res.*, 2014, **875-877**, 130-134, doi: 10.4028/www.scientific.net/AMR.875-877.130.
- [8] I. Janotka, A. Ray and S. Mojumdar, *Cement. Concrete. Res.*, 2003, **33**, 489-497, doi: 10.1016/S0008-8846(02)00994-8.
- [9] J. Péra and J. Ambroise, *Cement. Concrete. Res.*, 2004, **34**, 671-676, doi: 10.1016/j.cemconres.2003.10.019.
- [10] P. Xue, A. Xu, D. He, Q. Yang, G. Liu, F. Engström and B. Björkman, *Constr. Build. Mater.*, 2016, **122**, 567-576, doi: 10.1016/j.conbuildmat.2016.06.098.
- [11] S. Du, *Mater. Struct.*, 2014, **47**, 1149-1159, doi: 10.1617/s11527-013-0118-1.
- [12] R. Wang, X. G. Li and P. M. Wang, *Cement. Concrete. Res.*, 2006, **36**, 1744-1751, doi: 10.1016/j.cemconres.2006.05.020.
- [13] J. Pourchez, P. Grosseau and B. Ruot, *Cement. Concrete. Res.*, 2010, **40**, 179-188, doi: 10.1016/j.cemconres.2009.10.008.
- [14] M. Gretz and J. Plank, *Cement. Concrete. Res.*, 2011, **41**, 184-190, doi: 10.1016/j.cemconres.2010.11.005.
- [15] C. Lu, M. Kuo and D. Shen, *Constr. Build. Mater.*, 2009, **23**, 2580-2585, doi: 10.1016/j.conbuildmat.2009.02.014.
- [16] C. Chern and Y. Chen, *Colloid Polym. Sci.*, 1997, **275**, 124-130, doi: 10.1007/s003960050061.
- [17] M. Okubo, A. Yamada and T. Matsumoto, *J. Polym. Sci.*, 1980, **18**, 3219-3228, doi: 10.1002/pol.1980.170181108.
- [18] X. Kong, S. Emmerling, J. Pakusch, M. Rueckel and J. Nieberle, *Cement. Concrete. Res.*, 2015, **75**, 23-41, doi: 10.1016/j.cemconres.2015.04.014.
- [19] X. Yang, J. Liu, H. Li and Q. Ren, *Constr. Build. Mater.*, 2020, **235**, 117532, doi: 10.1016/j.conbuildmat.2019.117532.
- [20] O. Yilmaz, C. Cheaburu, G. Gülümser and C. Vasile, *Eur. Polym. J.*, 2012, **48**, 1683-1695, doi: 10.1016/j.eurpolymj.2012.07.010.
- [21] C. Zhao, J. Tan, W. Li, K. Tong, J. Xu and D. Sun, *Langmuir*, 2013, **29**, 14421-14428, doi: 10.1021/la4035535.
- [22] Y. Ishikawa, Y. Katoh and H. Ohshima, *Colloid. Surface. B*, 2005, **42**, 53-58, doi: 10.1016/j.colsurfb.2005.01.006.
- [23] G. B. Gao, S. T. Yan, Y. W. Wang and C. B. Liu, *Adv. Mater. Res.*, 2012, **450-451**, 543-547, doi: 10.4028/www.scientific.net/AMR.450-451.543.
- [24] M. Zajac, J. Skocek, F. Bullerjahn and M. B. Haha, *Cement. Concrete. Res.*, 2016, **84**, 62-75, doi: 10.1016/j.cemconres.2016.02.014.
- [25] H. Li, Z. Jiang, X. Yang, L. Yu, G. Zhang, J. Wu and X. Liu, *J. Clean. Prod.*, 2015, **93**, 56-64, doi: 10.1016/j.jclepro.2015.01.027.
- [26] T. Muhua and D. M. Roy, *Cement. Concrete. Res.*, 1987, **17**, 983-994, doi: 10.1016/0008-8846(87)90086-X.
- [27] C. Jolicoeur and M. A. Simard, *Cement. Concrete. Comp.*, 1998, **20**, 87-101, doi: 10.1016/S0958-9465(97)00062-0.
- [28] D. Jiao, C. Shi, Q. Yuan, X. An, Y. Liu and H. Li, *Cement. Concrete. Comp.*, 2017, **83**, 146-159, doi: 10.1016/j.cemconcomp.2017.07.016.
- [29] L. Zhang and A. Zhang, *Adv. Mater. Res.*, 2014, **936**, 1409-1413, doi: 10.4028/www.scientific.net/AMR.936.1409.
- [30] M. Chen, B. Liu, L. Li, L. Cao, Y. Huang, S. Wang, P. Zhao, L. Lu and X. Cheng, *Compos. Part B-Eng.*, 2020, **186**, 107821, doi: 10.1016/j.compositesb.2020.107821.
- [31] M. Chen, L. Li, Y. Zheng, P. Zhao, L. Lu and X. Cheng, *Constr. Build. Mater.*, 2018, **189**, 601-611, doi: 10.1016/j.conbuildmat.2018.09.037.
- [32] F. Wang, Y. Liu and S. Hu, *Constr. Build. Mater.*, 2013, **42**, 146-151, doi: 10.1016/j.conbuildmat.2013.01.009.
- [33] Y. Ohama, *ACI Mater. J.*, 1987, **84**, 511-518, <https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/2463>
- [34] A. Beeldens, D. Van Gemert, Y. Ohama and L. Czarnecky, Integrated model of structure formation in polymer modified concrete, 11th International Congress on the Chemistry of Cement, Durban, South Africa, (2003) 11-16.
- [35] F. Rosa and M. Casquilho, *Fuel Process. Technol.*, 2012, **103**, 174-177, doi: 10.1016/j.fuproc.2011.09.004.
- [36] A. Beeldens, D. Van Gemert, H. Schorn, Y. Ohama and L. Czarnecki, *Mater. Struct.*, 2005, **38**, 601-607, doi: 10.1617/14215.
- [37] P. Andersen, D. Roy, J. Gaidis and W. Grace, *Cement. Concrete. Res.*, 1987, **17**, 805-813, doi: 10.1016/0008-8846(87)90043-3.
- [38] C. Z. Li, N. Q. Feng and R. J. Chen, *Cement. Concrete. Res.*, 2005, **35**, 867-873, doi: 10.1016/j.cemconres.2004.04.031.
- [39] K. Yoshioka, E. I. Tazawa, K. Kawai and T. Enohata, *Cement. Concrete. Res.*, 2002, **32**, 1507-1513, doi: 10.1016/S0008-8846(02)00782-2.
- [40] T. Zhang, S. Shang, F. Yin, A. Aishah, A. Salmiah and T. Ooi, *Cement. Concrete. Res.*, 2001, **31**, 1009-1015, doi: 10.1016/S0008-8846(01)00511-7.
- [41] L. Gu, H. Li, X. Yang, B. Dong and Z. Wen, *J. Environ. Manage.*, 2020, **255**, 109934, doi: 10.1016/j.jenvman.2019.109934.

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