View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Brunel University Research Archive

Water absorption and water/fertilizer retention performance of vermiculite modified sulphoaluminate cementitious materials

Laibo Li[a], Xiangming Zhou[b], Chenchen Gong[a,*], Lingchao Lu[a], Xinghua Fu[a], Wenhong Tao[a]

[a]Shandong Provincial Key Laboratory of Preparation and Measurement of Building Materials, University of Jinan, Jinan 250022, China

[b]Department of Mechanical, Aerospace and Civil Engineering, Brunel University, London, Uxbridge, Middlesex UB8 3PH, United Kingdom

Abstract

This paper investigated the effects of vermiculite on water absorption, water/fertilizer retention and basic physicochemical properties of sulfoaluminate cementitious materials for plant growing applications. Vermiculite was utilised to partially replace sulfoaluminate cement (SAC) for the preparation of a cementitious material with enhanced water absorption capacities and water/fertilizer retention properties which are essential for plant growing in a cement-based environment. Mercury intrusion porosimetry (MIP) and thermal analysis (TG-DSC) were employed to characterize the effects of vermiculite on the porosity and hydration products of hardened SAC-based pastes for plant growing. Hydration heat-evolution was introduced for the hydration process of SAC-based materials. Experimental results showed that SAC based materials delivered the best performance at a 20 wt.% vermiculite content. At this SAC replacement level, the water absorption rate of hardened SAC-based paste increased by 95.3% while the water retention capacity of the SAC-based hardened paste increased 13% at 120 h. In addition, other property enhancements were measured including reduction of the fertilizer pervasion rate by up to 15.3 wt.% , a 0.45 drop in the pore fluid alkalinity and the early-age compressive strength of up to 35.1MPa.

Key words: Water absorption; Water/fertilizer retention; Vermiculite; Sulfoaluminate cementitious materials; Planting concrete

1. Introduction

Porous concrete is a non-conventional type of concrete which incorporates high porosity and possesses multiple environmental benefits [1]. It has been found to possess superior water-purification, permeability, noise absorption and thermal insulation properties [2-5], leading to its application in permeable trenches, gullies and gutters [1], noise barriers [3,4] etc. At a more innovative level, porous concrete has been used as a plant bedding [6, 7], and has been appropriately named ‘planting concrete’.

Due to its high porosity, planting concrete as plant bedding has been evaluated as an economical and environmentally friendly alternative to traditional impervious hard concrete for the purpose of growing plants, conserving water and soil [8]. Generally, planting concrete consists of cementitious materials, coarse aggregate, water and admixtures. Among the components, cementitious material directly determines the water absorption capacity, the water and fertilizer retention capacities, the alkalinity and other relevant properties, making it indisputably one of the most important components of planting concrete.

The cementitious material can be divided into two main types: Portland cement (PC) and SAC-based cementitious materials. The major hydration products of PC are C-S-H and calcium hydroxide (CH) [9-11], while AFt ($C_3A\cdot 3C\$\cdot H_{32}$; C = CaO, A = Al_2O_3 , \$ = SO_3 , H = H_2O) and AFm ($C_3A\cdot C\$\cdot H_{12}$) are the main principle crystal products during the hydration of SAC [12-14]. Therefore the alkalinity of pore fluid of hydrated SAC is lower than PC [15-18], making it a favourable envir- onment for plant growth. In addition, the production of SAC has the advantage of a lower calcination temperature (~1250°C), lower CO_2 emissions and easier grinding with less energy required [19-24]. Furthermore, using SAC can shorten the construction period due to its rapid hardening and high strength gain [25-27]. Therefore, the use of SAC is more suitable as a cementitious material compared with OPC.

But the water absorption capacity, water and fertilizer retention properties of the hardened paste of traditional cementitious material still cannot meet plant growing demand. Plants living in planting concrete can often wither and die, defeating the primary purpose of a planting concrete. On the other hand, vermiculite has a high water absorption capacity and desirable water retention capacity [28]. The study of Kiyoshi Okadaet al. observed that mixing allophane with vermiculite could control various pore sizes, which was a very good strategy for enhancing the water retention capacity of planting concrete [28, 29]. Vermiculite is a hydrous phyllosilicate mineral consisting of a 2:1 layered structure, and possesses the ability to store water molecules and exchangeable cations in its interlayer space [30-32]. Each layer in vermiculite consists of octahedrally coordinated cations (typically Mg, Al and Fe) about 1 nm in thickness, sandwiched by tetrahedrally coordinated cations (typically Si and Al) [33, 34]. The interlayer space of vermiculite is characterized by adsorption, ion exchange, etc. [31]. According to the basic theory of ‘fertilizer moves with water’ [35, 36], vermiculite also has a desirable fertilizer retention capacity. So it was evident that vermiculite is suitable to improve the water absorption capacity, water/fertilizer retention properties of cementitious materials.

Therefore, in this paper, vermiculite was adopted to partially replace SAC in order to prepare a cementitious material with an enhanced water absorption capacity, water/fertilizer retention properties. At the same time, urea was adopted as the fertilizer to study the effect of vermiculite on the fertilizer retention property of SAC-based material. Another important intention of this study is to determine vermiculite's effect on the basic physicochemical properties and the mechanisms, such as alkalinity of pore fluid, pore structure, mechanical properties, thermo-gravimetric analysis and heat of hydration. The intention of this paper is to offer useful data to advance the knowledge in the planting concrete industry, especially for cementitious material.

2. Materials and Methods

2.1 Materials

SAC (42.5 R, manufactured in China) was used as the base cementitious material in this study, whose initial and final setting times were 15 min and 21 min, respectively. The exfoliated vermiculite from a local supplier, calcined at 850°C. The chemical compositions of SAC and vermiculite were determined by X-ray fluorescence spectrometer (Tiger S8, Bruker AXS GMBH, Germany), and are given in Table 1. Particle size distributions of SAC and vermiculite were determined using a laser particle size analyzer (LS13320, Beckman, USA) and are presented in Fig.1.

Urea (with a purity of 99.0 wt.%, from Damao Chemical Reagent Factory, China) was adopted as fertilizer in this study. The urea was composed of no more than 0.005 wt.% water-insoluble substances, had an ignition loss of no higher than 0.01 wt.%, and a burette content of no more than 0.2wt. %.

2.2 Experimental design

In this study, vermiculite was used to partially replace SAC at the replacement levels of 5%, 10%, 20% and 40% by weight and marked as SV 5, SV 10, SV 20 and SV 40, respectively. A control sample of SAC without vermiculite was named SV ref. The mix proportions of the investigated SAC-based cementitious materials are shown in Table 2.

2.3 Sample preparation

The pastes without fertilizer were prepared with a water-to-binder (W/B) weight ratio of 0.35, then cast in 20 × 20 × 20 mm^3 moulds and vibrated to remove air bubbles. The moulded pastes were kept in a curing environment of 20±2°C and 95+% RH. After 24 hours, the specimens were demoulded and then placed in water at 20±2 °C for 2 days. Subsequently, the hydration of the cement pastes was stopped by leaving samples immersed in absolute ethyl alcohol for 24h.

The pastes containing fertilizer were prepared and cured in the exact same conditions as described above, differentiating only in that fertilizer had been predissolved in the mixing water. The fertilizer contents used were 2%, 4% and 8% (by weight) of binder.

In this paper, mortars were adopted to study the mechanical property of cementitious materials, which were prepared and cured according to the Chinese National Standard GB 20472-2006 [37].

2.4 Test methods

2.4.1 Water absorption capacity

The water absorption capacities of the hardened pastes were tested at 35±2°C. The hardened pastes without fertilizer were cured for 3 days followed by drying at 35±2°C for 24h, after which they were accurately weighted and the mass recorded as m_0. Specimens were soaked in deionized water until the weight did not increase more than 0.1%. Samples were taken out from water and the surface water of the samples was gently dried to remove. Then the samples were accurately weighted and the mass was recorded as m_1. The Water Absorption Rate (WAR) of a sample was calculated as $WAR=[(m_1-m_0)/m_0]\times100\%$.

2.4.2 Water retention property

The samples after the water absorption test were exposed to an environment of 35±2°C and 20±2% RH. At predetermined times (0.5h, 1h, 2h, 4h, 6h, 8h, 10h, 15h, 20h, 25h, 30h, 40h, …, 80h, 100h, 120h), the samples were accurately weighed and the mass recorded as m_2. The water release rate (WRR) of a sample was calculated as $WRR=[(m_1-m_2)/(m_1- m_0)]\times100\%$.

2.4.3 Fertilizer retention capacity

The hardened pastes' fertilizer retention capacity is demonstrated by fertilizer release rate in deionised water. Every sample was soaked in 100ml deionized water. At predetermined times (1d, 2d, … , 7d, 10d, 14d, 21d, 28d, 35d), the fertilizer concentration of the soaking solution was tested by ultraviolet-visible spectroscopy (UV-VIS) [38]. After each test, the soaking water was replaced by another 100ml pure deionised water.

2.4.4 Alkalinity of pore fluid

For this test, ex-situ leaching [39] was adopted to prepare the pore liquid. The pH was tested by using a laboratory grade pH meter (Spsic, PHS-3E, China).

2.4.5 TG-DSC analysis

TG-DSC analysis was conducted to estimate quantitatively the hydration product content, especially the CH content using a simultaneous thermal analyzer (Mettler, TGA/DSC1/1600HT, Sweden) at a heating rate of 20°C/min from 0°C to 800°C under argon atmosphere.

2.4.6 Mechanical properties

The mechanical properties of the samples were tested according to the Chinese National Standard GB20472-2006[37].

2.4.7 Hydration heat evolution

A conduction calorimeter (TAM Air C80, Thermometric, Sweden) operating at 25°C was used to determine the hydration heat flow. For such purpose, a water to binder of 0.5 was adopted, and the heat flow was recorded every 44s until 72h.

2.4.8 Bulk density

The bulk density of hardened paste specimens was measured by the water vacuum saturation method [40, 41]. The specimens were dried at 65°C in order to remove the majority of the physically bound water. After that, the hardened pastes were placed into a desiccator with deaired water. For the duration of three hours, air was evacuated with a vacuum pump from the desiccator. The hardened pastes were then kept in water for more than 24h.

2.4.9 Pore structure

Mercury intrusion porosimetry was employed to examine the pore structure of hardened pastes. An automatic mercury porosimetry (Pore Master-60, Quanta- chrome Instruments, USA) was used in this study, whose intrusion accuracy was ±0.11%.

3. Results and Discussion

3.1 Planting potential

3.1.1 Water absorption capacity

The WARs of hardened pastes are shown in Table 3. The WAR of SV ref was only 8.05wt.%. When the dosage of vermiculite was 5 wt.%, the WAR increased by 16.8% to a value of 9.40 wt.%. Evidently, with the increase of vermiculite dosage, the WAR increased. This trend continued with the increase of vermiculite dosage. With an addition of 20 wt.% vermiculite, the WAR reached up to 14.82 wt.%, an increase of 84.1% compared to the SV ref. Therefore vermiculite proved to be suitable to improve the water absorption capacity of cementitious material pastes.

3.1.2 Water retention capacity

The measured water release rates of hardened pastes are presented in Fig.2, representing their water retention capacity. When the exposure time was less than 8h, the water release rate of pastes increased with the increasing of vermiculite dosage. A possible reason was that with the increase of vermiculite dosage, the open porosity at sample surfaces increased, resulting the amount of free water at sample surfaces to increase. The water release rate of SV ref reached up to 98.9% at 120h. At the same time, the water release rate of SV 20 was only 80.4%, suggesting that vermiculite could improve water retention capacity of cementitious pastes. This enhancement can be attributed to the increased internal porosity imparted by vermiculite.

3.1.3 Fertilizer retention capacity

The fertilizer release rates from hardened pastes are presented in Fig.3, which represent the fertilizer retention property. The fertilizer release rates increased with the increase of soaking time. The fertilizer release rate of SV ref at 35d was highest and reached up to 96.3 wt.% when fertilizer dosage was 20 wt.% (Fig.3 (a)), suggesting that the fertilizer added during mixing could be released slowly in the hardened pastes. And the fertilizer release rate grew with a straight-line at early ages (i.e. up to 7d) and with the further extending of soaking time the curves of fertilizer release rate became flatten, indicating that the velocity of fertilizer release decreased with the increase of soaking time.

In this study, in cases of a vermiculite content of less than 20wt.%, the fertilizer release rate from hardened pastes decreased with the increase of vermiculite content at the same soaking times. For example, in Fig.3(b) the 35d fertilizer release rate of SV 5, SV10 and SV 20 were 62.9 wt.%, 60.2 wt.% and 54.3 wt.% lower than that of SV ref. However, 40 wt.% vermiculite could increase the fertilizer release rate of hardened pastes compared with SA ref with 0 wt.% vermiculite, which suggests that excessive vermiculite is not beneficial to the fertilizer retention property of cementitious materials. Therefore vermiculite dosage should be less than 20 wt.%, which could improve the fertilizer retention capacity of an SAC-based cementitious material.

In addition, there was a phenomenon worthy noting here. When using a fertilizer dosage of 8 wt.% at most, for the same kind of materials, the fertilizer release rates decreased with the increase of fertilizer addition. Therefore, a proper fertilizer dosage could also improve the fertilizer retention property of cementitious materials.

3.1.4 Alkalinity

Fig.4 shows the alkalinity of pore fluid of hardened cementitious pastes. A previous study [42] demonstrated that the pH of pore fluid of hardened PC paste was about 13 as determined by ex-situ leaching. In this study, the pH of pore fluid of SV ref was 11.40, which is significantly less than that of PC. The pH of pore fluid of the hardened pastes decreased gradually with the increase of vermiculite dosage, and the pH of SV 20 and SV 40 was measured to be 10.95 and 10.71, respectively. Therefore, vermiculite could effectively reduce the alkalinity of pore fluid of hardened SAC-based materials. This result further proves that SAC-based cementitious materials with vermiculite are suitable to prepare planting concrete.

The TG-DSC analyses of the hydration products are shown in Fig.5. The TG-DSC curves (Fig.5 (a)) of SV 20 and SV 40 became gentler compared with that of SV ref. at 400°C~500°C which was the decomposition temperature of CH [43]. According to TG-1st derivative curve (Fig.5 (b)), the area of the endothermic peak of SV ref was less than that of SV ref at 400°C~500°C and no corresponding peak was seen in that of SV 40. These suggested that the CH content of hardened pastes was decreased by vermiculite. As increased amounts of SAC were replaced by vermiculite, this reduced the amount of CH that could potentially form from the hydration of SAC.

Furthermore, the total pore volume and pore liquid content increased with the increase of vermiculite dosage, which decreased the concentrations of Ca^{2+} and OH^- of pore fluid of hardened pastes. The formation and growth of CH crystals were limited. Therefore, the alkalinity of pore fluid of hardened pastes decreased with the increase of vermiculite content. Therefore, it was concluded that vermiculite played a positive role during the hydrating of the cementitious materials to reduce alkalinity. Low alkalinity was helpful for plant growing in planting concrete and achieved the expected value in this study.

3.2 Basic physicochemical properties

3.2.1 Mechanical properties

The mechanical properties of SAC-based cementitious materials are presented in Fig.6. The compressive strength (Fig.6 (a)) and flexural strength (Fig.6 (b)) decreased with the increase of vermiculite dosage. The 1d, 3d and 28d compressive strength of SV ref reached up to 38.1, 45.5 and 51.5 MPa, respectively and the 1d, 3d and 28d flexural strength reached up to 5.9, 7.8 and 8.1 MPa, respectively. For SV 5 at 1d, 3d, and 28d, the compressive strength was 36.5, 41.5 and 48.7 MPa, respectively, while flexural strengths of 5.6, 7.5, and 7.7 MPa, respectively, was attained at the same curing ages. So there was minor effect of 5 wt.% vermiculite on mechanical property of SAC-based materials. The 1d and 3d compressive strength of SV 20 were 28.5 and 35.1 MPa, respectively.

Compared to SV ref, the 1d and 3d compressive strength of SV 20 reduced 25.2% and 22.9%, respectively. Furthermore, the 3d compressive and flexural strength of SV 40 reduced to 19.4 and 4.1 MPa, respectively. The 3d compressive strength and flexural strength of SV 40 reduced 57.4% and 47.4% compared with the corresponding value of SV ref. Therefore, a dosage of 40 wt.% vermiculite was very negative to the mechanical property of SAC-based materials.

3.2.2Hydration heat evolution

Fig.7 shows the hydration heat evolution of SAC-based cementitious materials. There was minor effect of vermiculite addition on the first exothermic peak (heat of dissolution, the age of about 0.1h) of SAC-based materials. The second exothermic peak (the age of about 1h) decreased with the increase of vermiculite content, which was caused by the hydration of ye'elimite ($C_4A_3\$$) and the main hydration product was Aft ($C_4A_3\$ + 2C\$ + 38H \rightarrow C_3A\cdot 3C\$\cdot H_{32} + 2AH_3$). The third exothermic peak (at the age between 2 and 5h) was $C_4A_3\$$ hydrate which produces Aft ($C_4A_3\$ + 2C\$ + 38H \rightarrow C_3A\cdot 3C\$\cdot H_{32} + 2AH_3$), and the time between the second and the third exothermic peak became gradually longer with the increase of vermiculite dosage. The delay of the onset of the third peak has been considered as the induction period of the hydration of $C_4A_3\$$. Therefore, it can be concluded that vermiculite can increase the induction period of the hydration of $C_4A_3\$$. Presumably, it was caused by the increased water absorption by vermiculite. In addition, the fourth exothermic peak (at the age about 5h), which represents the hydration of $C_4A_3\$$ to produce AFm ($C_4A_3\$ + 18H \rightarrow C_3A\cdot C\$\cdot H_{12} + 2AH_3$), increased with the increase of vermiculite content.

Furthermore, the 1d and 3d cumulative heats of SV 5 and SV 10 were similar to those of SV ref. So there was negligible effects of 5 wt.% and 10 wt.% vermiculite content on the 1d and 3d cumulate heat of SAC-based materials. So 1d and 3d mechanical properties of SV 5 and SV 10 were similar to those of SV ref. In addition, the 1d and 3d cumulate heats of SV 20 were slightly lower than those of SV ref. Also, the 1d and 3d cumulate heats of SV 40 were significantly lower than those of SV ref. Therefore the 1d and 3d mechanical properties of SV 40 were significantly lower than those of SV ref. It was because that 40 wt.% SAC had been replaced by vermiculite.

3.2.3 Pore structure

The cumulative pore volumes of hardened pastes are shown in Fig.8. The total pore volume of SV ref was only 9.0%, which can be attributed to its poor water absorption capacity. The total pore volume increased with the increase of vermiculite dosage, which was probably due to the difference in the particle size between SAC and vermiculite (Fig.1). Hence the water absorption capacity increased with the increase of vermiculite dosage. Compared to SV ref, the total pore volume of SV 10 and SV 20 increased by 31.1% and 66.7%, respectively. Therefore, vermiculite was able to improve the total pore volume of hardened SAC-based pastes.

Fig.9 presents the pore size distribution of hardened pastes. While the vermiculite content was no more than 20 wt.%, the increase of pore volume was mainly due to fine pores between 0.4 and 1μm in diameter. Generally, the water retention property can be enhanced by various pore sizes [29]. Therefore, the water retention property was improved by vermiculite as long as the vermiculite dosage is no more than 20 wt.%. However with a vermiculite dosage of 40 wt.%, the volume of pores between 0.2~1μm in diameter decreased while the volumes of 10~30μm and 100~200μm pores significantly increased, which were harmful to the water/fertilizer retention property and mechanical performance. So vermiculite addition could cause pore volume and pore size changed. The latter results explain the change of water absorption capacity, water/fertilizer retention property and mechanical performance of hardened SAC pastes prepared with varying dosages of vermiculite.

The bulk densities of hardened pastes are shown in Fig.10. In this study, the bulk density of hardened pastes decreased with the increase of vermiculite. The bulk density of SV ref reached up to 1.86 g/cm^3, while the bulk density of SV 20 was only 1.72 g/cm^3. Compared to SV ref, the bulk density of SV 20 reduced 7.5%. When the dosage of vermiculite reached to 40 wt.%, the bulk density of hardened pastes further reduced to 1.61 g/cm^3 and was 13.4% lower than that of SV ref. So, vermiculite was beneficial to decrease the bulk density of hardened pastes. In addition, these also probably suggested that the compactness of hardened pastes decreased with the increase of vermiculite dosage. In other words, the porosity of hardened pastes increased with the increase of vermiculite dosage.

The relationships between total pore volume, WAR and bulk density of hardened pastes are shown in Fig.11. The correlation coefficient between total pore volume and WAR reached up to 0.9981, which proved that there was an extremely significant linear correlation between them. Furthermore, the water absorption capacities of SV ref, SV 5, SV 10, SV 20 and SV 40 were 8.05wt.%, 9.40wt.%, 11.20wt.%, 14.82wt.%, and 17.81wt.%, respectively. Water with a density of about 1g/cm^3 was used in all mixtures, so the water absorption capacities can be approximately expressed for SV ref, SV 5, SV 10, SV 20 and SV 40 as 0.081, 0.094, 0.112, 0.148 and 0.178 cm^3/g, respectively. Additionally, the total pore densities of SV ref, SV 5, SV 10, SV 20 and SV 40 were 0.090, 0.102, 0.118, 0.150 and 0.175 cm^3/g, respectively. Therefore, the difference between water absorption and total pore volume decreased with the increase of vermiculite dosage. Those proved that the reason for the water absorption rate increased with the increase of vermiculite addition was not only due to the increase of pore volume, but vermiculite also has excellent water absorption property. Because vermiculite has 2:1 (tetrahedral–octahedral–tetrahedral) type layered structure, weak bond existed between the layers of vermiculite molecular structure. So water is able to enter the layers of vermiculite molecular structure.

In addition, the correlation coefficient of total pore volume and bulk density of hardened pastes reached up to 0.9736. It proves that the bulk density decreasing with the increase of vermiculite dosage was because the total pore volume increased with the increase of vermiculite content once again.

4. **Conclusions**

In this paper, from the basis of multiple perspectives, the effects of vermiculite on water/fertilizer retention and basic physicochemical properties of SAC-based materials were investigated. The main conclusions that can be drawn are as following:

(1) The water absorption capacity of hardened SAC-based materials increased with the increase of vermiculite dosage. The water absorption capacity was improved 81.8% using 20 wt.% vermiculite.

(2) The adoption of vermiculite proved to be suitable for the enhancement of the water retention property of SAC-based materials when its dosage is no more than 20 wt.%. At 120h, the water release rate decreased by 18.5% at 20 wt.% vermiculite replacement level.

(3) The change of the fertilizer retention property of SAC-based material was similar to that of water retention property, because 'fertilizer moves with water'. 20 wt.% vermiculite in the SAC-based materials was the best therapy for improving fertilizer retention. For the latter cement replacement level, the fertilizer release rate at 35d reduced 15.3 wt.% and 12.1 wt.% when the fertilizer dosage was 2 wt.% and 4 wt.%, respectively.

(4) Vermiculite can decrease the pore fluid alkalinity of hardened SAC-based pastes. The alkalinity of pore fluid of hardened pastes reduced 0.45 at 20 wt.% vermiculite dosage, which is beneficial for plant growth.

(5) The compressive strength and flexural strength decreased with the increase of vermiculite dosage. However, the 3d compressive strength and 3d flexural strength of SV 20 reached up to 35.1 and

6.0MPa, respectively, which can meet the requirement for planting concrete.

(6) The total pore volume of hardened SAC-based materials increased with the increase of vermiculite. The total pore volume increased 6% when 20wt.% vermiculite was incorporated. The increase of pore volume was mainly due to vermiculites' fine pores of diameter between 0.4~1μm.

Acknowledgments

This work was supported by the National Natural Science Foundation of China through the grants of NO.51302104 and NO.51472109, and Science and Technology Development Plan of Shandong Province through the grant of NO.2014GZX208001. In addition, this work was also supported by the Program for Scientific Research Innovation Team in Colleges and Universities of Shandong Province.

Reference

[1] M. Aamer Rafique Bhutta, K. Tsuruta, J. Mirza. Evaluation of high-performance porous concrete properties. Constr and Build Mater. 2012;31: 67–73.

[2] P. Sung-Bum , T. Mang. An experimental study on the water-purification properties of porous concrete. Cem Concr Res. 2004;34:177–184.

[3] K. Ćosić, L. Korat , V. Ducman , I. Netinger. Influence of aggregate type and size on properties of pervious concrete. Constr and Build Mater. 2015;78: 69–76.

[4] H. K. Kim, H. K. Lee. Acoustic absorption modeling of porous concrete considering the degradation and shape of aggregates and void ratio. J. Sound Vib. 2010;329:866–879.

[5] A. S. Agar–Ozbek, J. Weerheijm, E. S. K. Breugel. Investigating porous concrete with improved strength: Testing at different scales. Constr and Build Mater. 2013;41:480-490.

[6] M. Tarnai, H. Mizuguchi. Design, construction and recent applications of porous concrete in Japan. In: Proceedings of the JCI symposium on design, construction and recent applications of porous concrete, Japan Concrete Institute, Tokyo. 2004;4:1–10.

[7] M. A. R. Bhutta, N. Hasanah. Properties of porous concrete from waste crushed concrete (recycled aggregate). Constr and Build Mater. 2013;47:1243–1248.

[8] X. Yan, C. Gong, S. Wang, L. Lu. Effect of aggregate coating thickness on pore structure features and properties of porous ecological concrete. Mag Concr Res. 2013;65(1):1–8.

[9] Z. Keren, Z. Jin, G. Mulbah. Influences of phosphate tailings on hydration and properties of Portland cement. Constr and Build Mater. 2015;98:593–601.

[10] M. R. Meier, M. Sarigaphuti, P. Sainamthip, J. Plank. Early hydration of Portland cement studied under microgravity conditions. Constr and Build Mater. 2015;93:877–883.

[11] R. Kaminskas, V. Cesnauskas, R. Kubiliute. Influence of different artificial additives on Portland cement hydration and hardening. Constr and Build Mater. 2015;95:537–544.

[12] L. H. J. Martin, F. Winnefeld, C. J. Müller, B. Lothenbach. Contribution of limestone to the hydration of calcium sulfoaluminate cement. Cem Concr Comp. 2015;62:204–211.

[13] S. W. Tang, H. G. Zhu, et al. Hydration stage identification and phase transformation of calcium sulfoal- uminate cement at early age. Constr and Build Mater. 2015;75:11–18.

[14] M. Juenger, F. Winnefeld, J. Provis, J. Ideker. Advances in alternative cementitious binders. Cem Concr Res. 2011;41:1232–43.

[15] F. Winnefeld, B. Lothenbach. Hydration of Calcium Sulfoaluminate Cements—Experimental Findings and Thermodynamic Modelling. Cem Concr Res. 2010;40(8):1239–1247.

[16] S. Meimei, P. Purnell, I. Richardson. Microstructure of interface between fibre and matrix in 10-year aged GRC modified by calcium sulfoaluminate cement. Cem Concr Res. 2015;76:20–26.

[17] A. Telesca, M. Marroccoli. A hydration study of various calcium sulfoaluminate cements. Cem Concr Comp. 2014;53:224–232.

[18] M. García-Maté, A. G. De la Torre. Hydration studies of calcium sulfoaluminate cements blended with fly ash. Cem Concr Res. 2013;54:12–20

[19] Z. Xiong, Z. Ming, Z. Yongjuan. Preparation and properties of self-pulverizing calcium sulfoaluminate cement. Constr and Build Mater. 2012;34:107–113.

[20] M. Marie, G. Jean-François, A. Jean. Improving the mechanical performance of high-grade slag cement by the addition of Portland cement and sulfoaluminate cement. Constr and Build Mater. 2012;37:291–300.

[21] X. Dong, S. Wang, C. Gong, L. Lu. Effects of aggregate gradation and polymer modifyers on properties of cement-EPS/vitrified microsphere mortar. Constr and Build Mater. 2014; 73:255– 260.

[22] M. García-Maté, A. G. D. Torre. Hydration studies of calcium sulfoaluminate cements blended with fly ash. Cem Concr Res. 2013;54:12–20.

[23] M. Marie, G. Jean-François, A. Jean. Improving the mechanical performance of high-grade slag cement by the additionof Portland cement and sulfoalum- inate cement. Constr and Build Mater. 2012;37: 291–300.

[24] S. Berger, G. Aouad. Leaching of calcium sulfoaluminate cement pastes by water at regulated pH and temperature: experimental investigation and modeling. Cem Concr Res. 2013;53:211–220.

[25] Y. Liao, X. Wei, G. Li. Early hydration of calcium sulfoaluminate cement through electrical resistivity measurement and microstructure investigations. Constr and Build Mater. 2011;25: 1572–1579.

[26] G. Bernardo, A. Telesca, G. L. Valenti. A porosimetric study of calcium sulfoaluminate cement pastes cured at early ages. Cem Concr Res. 2006;36:1042– 1047.

[27] R. Trauchessec, J. M. Mechling, et al. Hydration of ordinary Portland cement and calcium sulfoaluminate cement blends. Cem Concr Comp. 2015;56: 106–114.

[28] K. Okada, S. Matsui, T. Isobe, et al. Water-retention properties of porous ceramics prepared from mixtures of allophane and vermiculite for materials to counteract heat island effects. Ceram Int. 2008; 34:345–350.

[29] M. Valášková, G. Simha Martynková, B. Smetana, S. Študentová. Influence of vermiculite on the formation of porous cordierites. Appl Clay Sci 2009;46: 196–201

[30] E. S. Pouya, H. Abolghasemi, et al. Batch adsorptive removal of benzoic acid from aqueous solution on to modified natural vermiculite: Kinetic, isotherm and thermodynamic studies. J Ind Eng Chem. 2015;31: 199–215.

[31] W. Nian, W. Limei, L. Libing, L. Guocheng. Organic intercalation of structure modified vermiculite. J Colloid Interf Sci. 2015;457:264–271.

[32] W. Yang, Y. Zheng, A. Zaoui. Swelling and diffusion behaviour of Na-vermiculite at different hydrated states. Solid State Ionics. 2015; 282: 13–17.

[33] C. Marcos, I. Rodríguez. Expansion behaviour of commercial vermiculites at 1000 °C. Appl Clay Sci. 2010;48:492–498.

[34] D. Jaroslaw, L. Bowen, et al. Vermiculite decorated with copper nanoparticles: Novel antibacterial hybrid material. Appl Surf Sci. 2011;257:9435– 9443.

[35] E. E. Alberts, W. C. Moldenhauer. Nitrogen and phosphorus transported by eroded soil aggregates. Soil Sci Soc Am J. 1981; 45(2):391-396.

[36] X. Li, Z. Zhang, J. Yang, G. Zhang, B. Wang. Study on the nutrition loss in subsurface runoff under different ecological measures on red soil slope. J Water Res & Water Eng. 2010;21(2): 83-86. (in Chinese)

[37]GB (2006) GB/T 20472-2006: Sulfoaluminate cement. Standarization Administration of the People's Republic of China, Beijing, China. (in Chinese)

[38] GB (2010) GB/T 2441.1-2010: Determination of urea-Spectrophotometry method. Standarization Administration of the People's Republic of China, Beijing, China. (in Chinese)

[39] L. Li, J. Nam, H. H. William. Ex situ leaching measurement of concrete alkalinity. Cem Concr Res. 2005;35(2):277–283.

[40] E. Vejmelková, D. Koňáková, et al. Engineering properties of concrete containing natural zeolite as supplementary cementitious material: Strength, toughness, durability, and hygrothermal performance. Cem Concr Comp. 2015; 55:259-267.

[41] S. Roels, J. Carmeliet, et al. Inter laboratory comparison of hygric properties of porous building materials. J Therm Envelope Build Sci. 2004;27: 307–25.

[42] M. Codina, C. C. Coumes, et al. Design and characterization of low–heat and low–alkalinity cements. Cem Concr Res. 2008;38(4):437–448.

[43] W. Yongqi, Y. Wu, X. Xiaoming, W. Manjian. Quantitative evaluation of hydrated cement modified by silica fume using QXRD, ^{27}Al MAS NMR, TG–DSC and selective dissolution techniques. Constr and Build Mater. 2012;36:925–932.

Fig.1

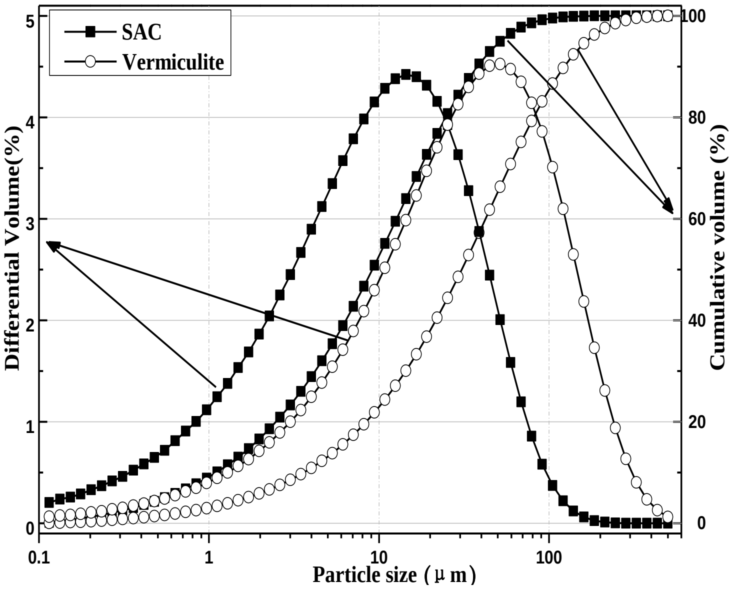


Fig.1 Particle size distributions of SAC and vermiculite

Fig.2

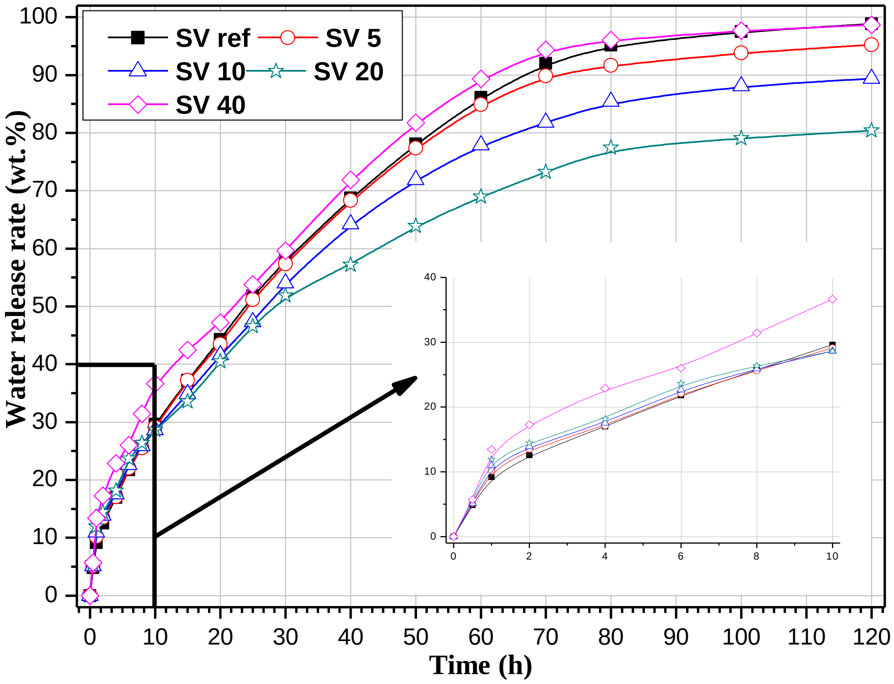
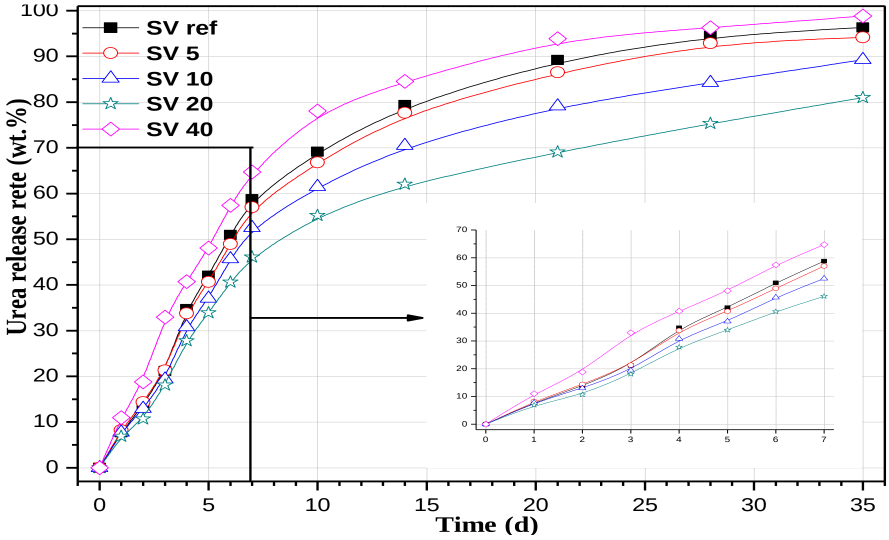
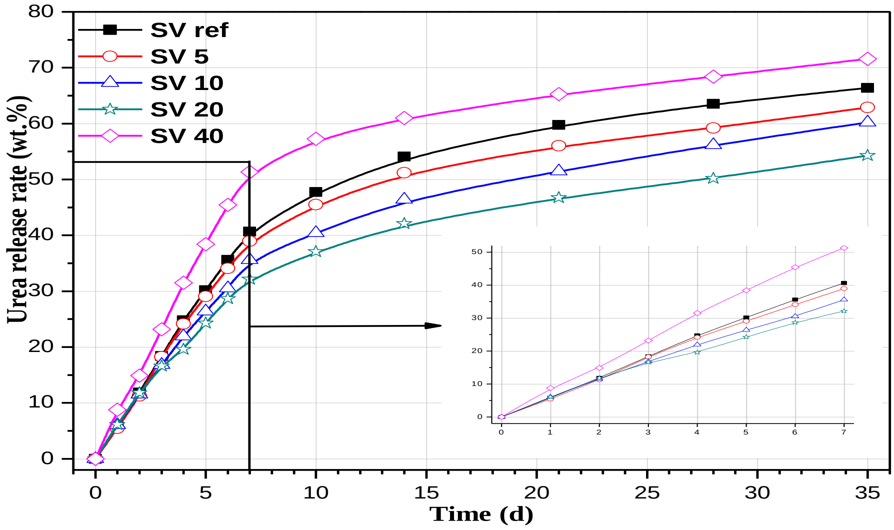


Fig.2 Water release rate of hardened pastes

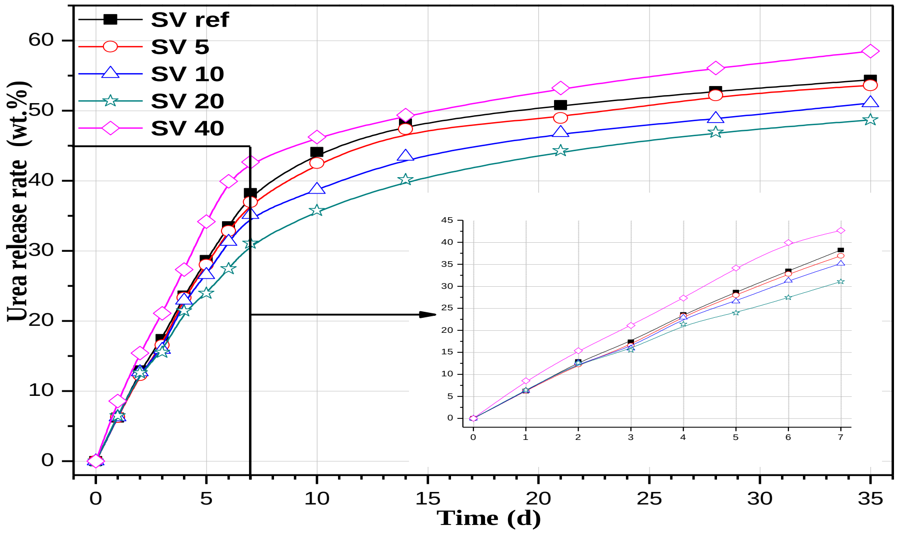
Fig.3



(a) Fertilizer dosage of 2 wt. %



(b) Fertilizer dosage of 4 wt. %



(c) Fertilizer dosage of 8 wt. %

Fig.3 Fertilizer release rate of hardened pastes

Fig.4

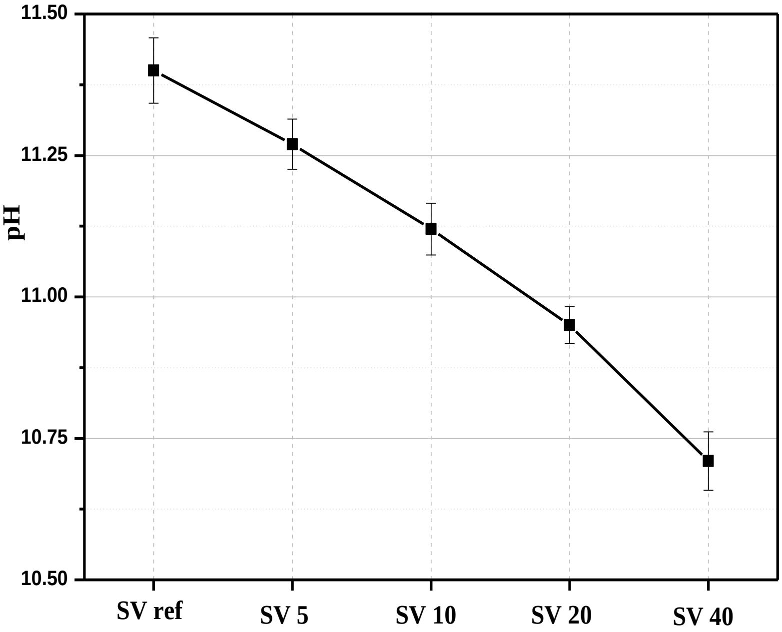
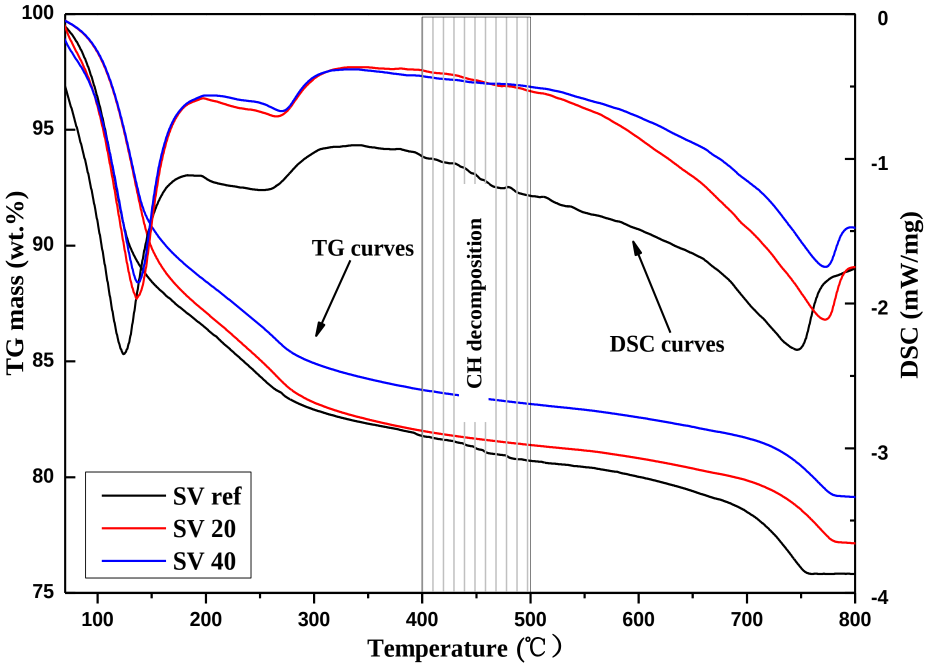
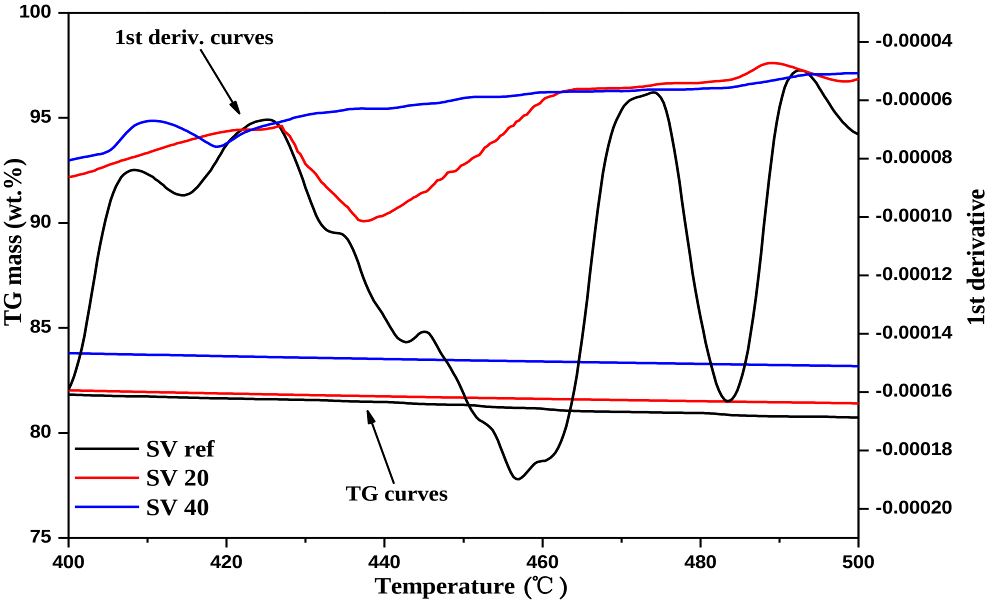


Fig.4 Alkalinity of pore fluid of hardened pastes

Fig.5



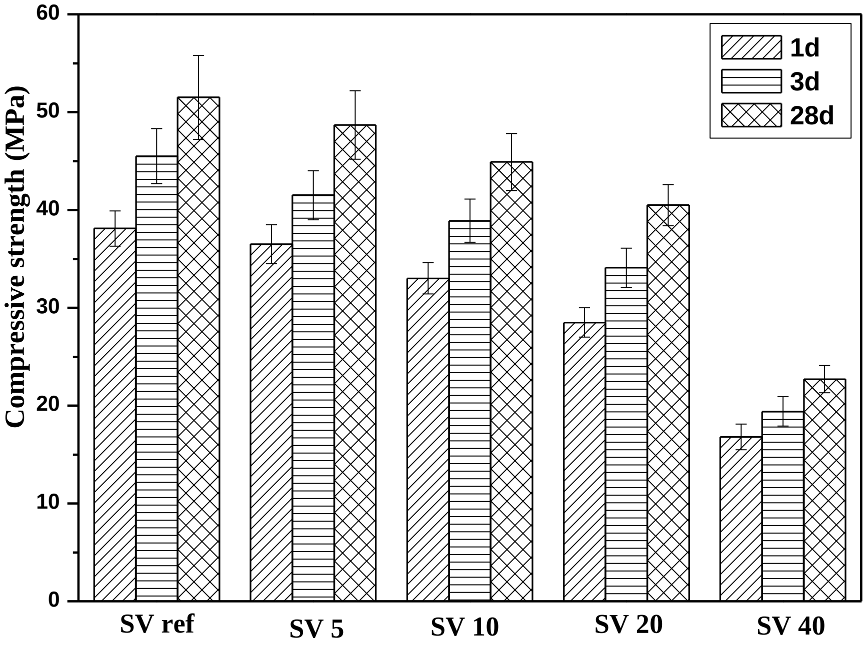
(a) TG-DSC curves



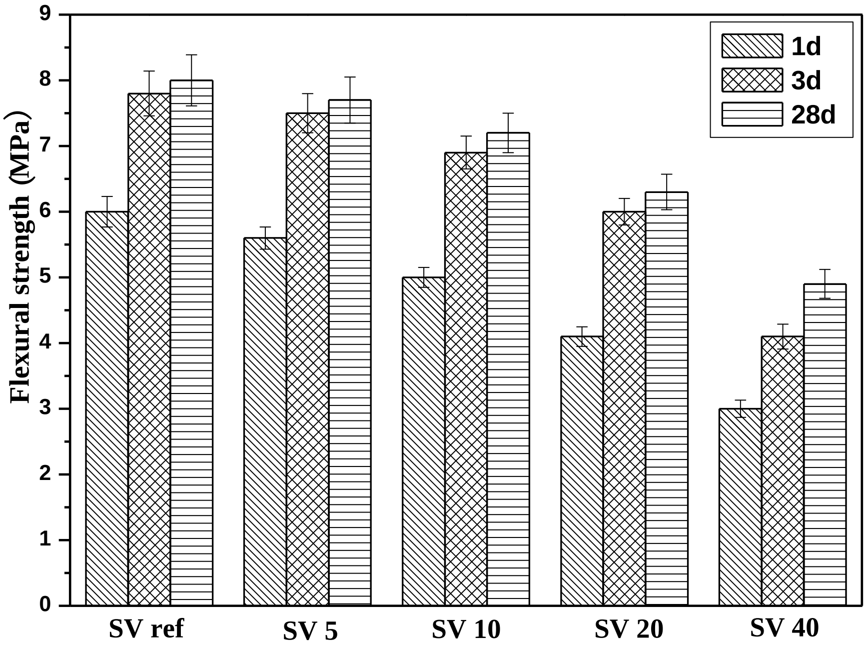
(b) TG-1st curves

Fig. 5 TG-DSC analysis

Fig.6



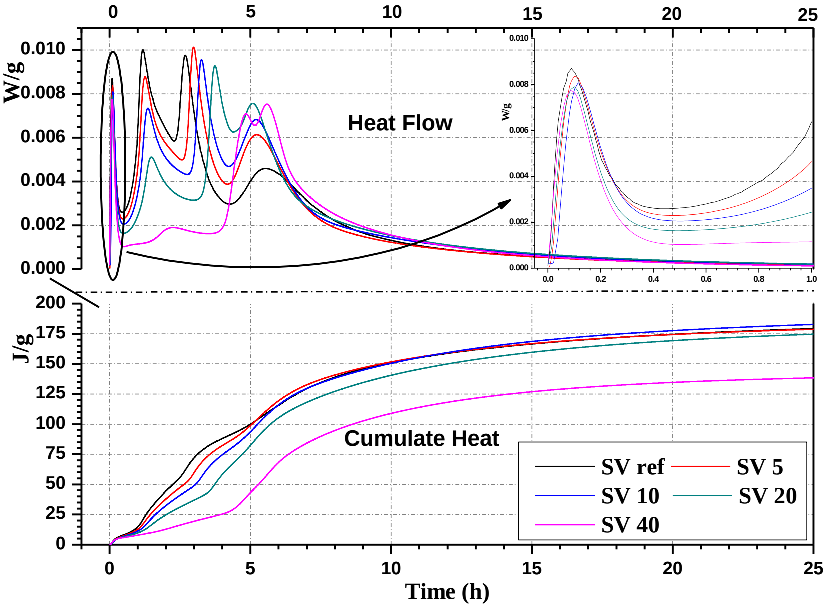
(a) Compressive strength



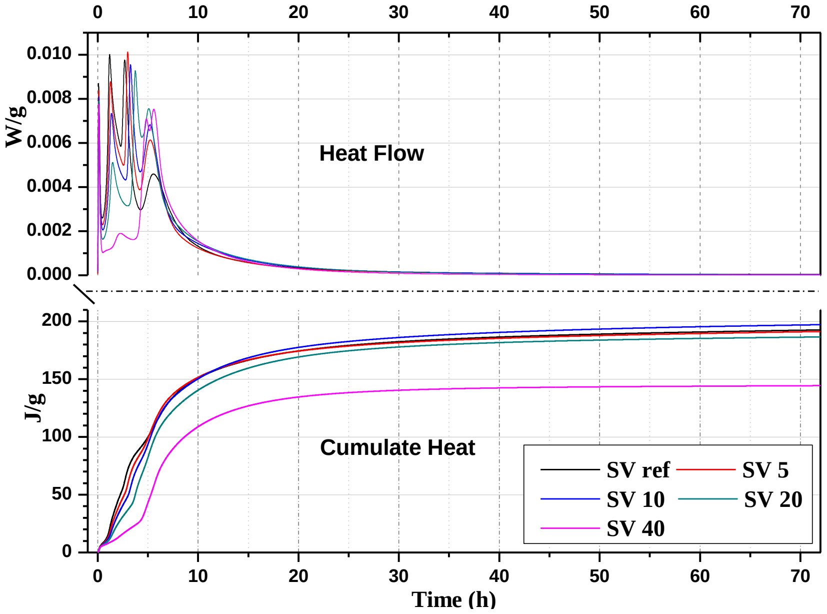
(b) Flexural strength

Fig.6 Mechanical properties of cementitious materials

Fig.7



(a) hydration heat evolution for 1d



(b) Hydration heat evolution for 3d

Fig.7 Hydration heat evolution

Fig.8

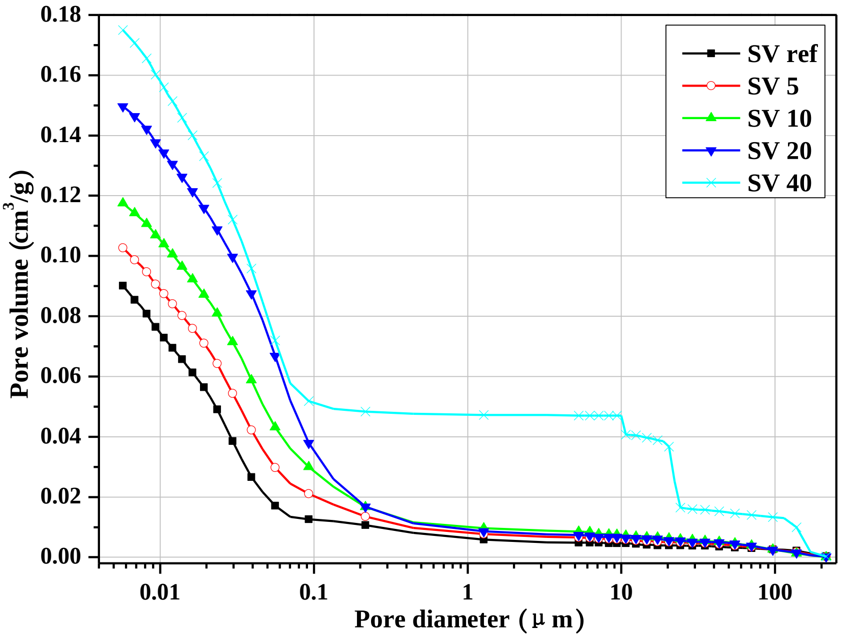


Fig.8 Cumulative pore volume of hardened pastes

Fig.9

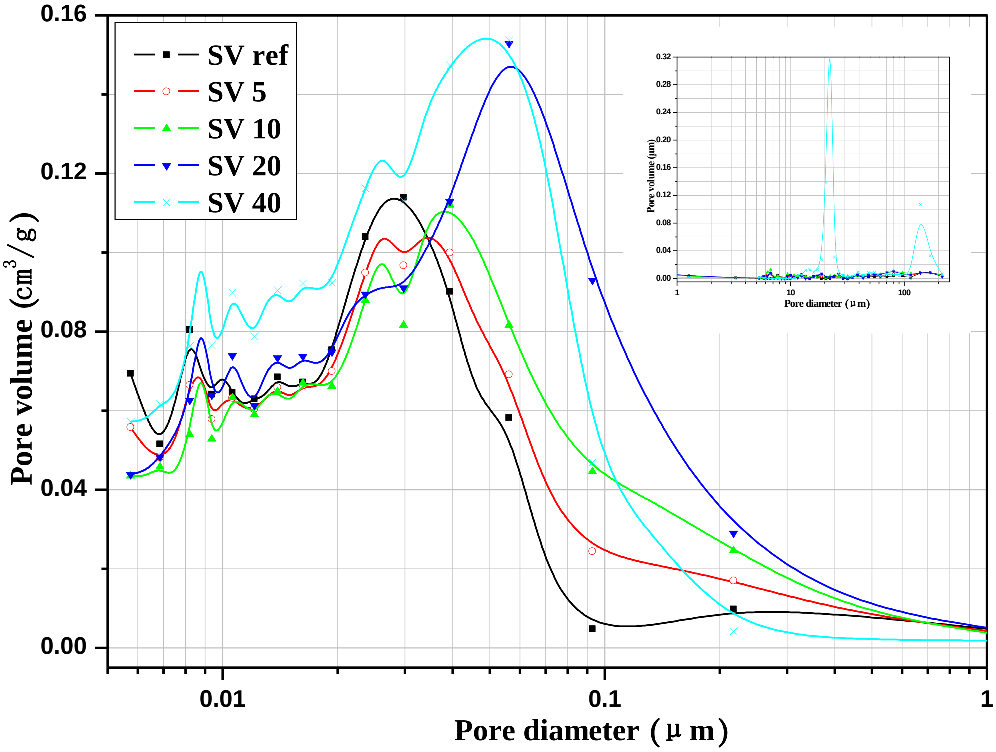


Fig.9 Pore size distribution of hardened pastes

Fig.10

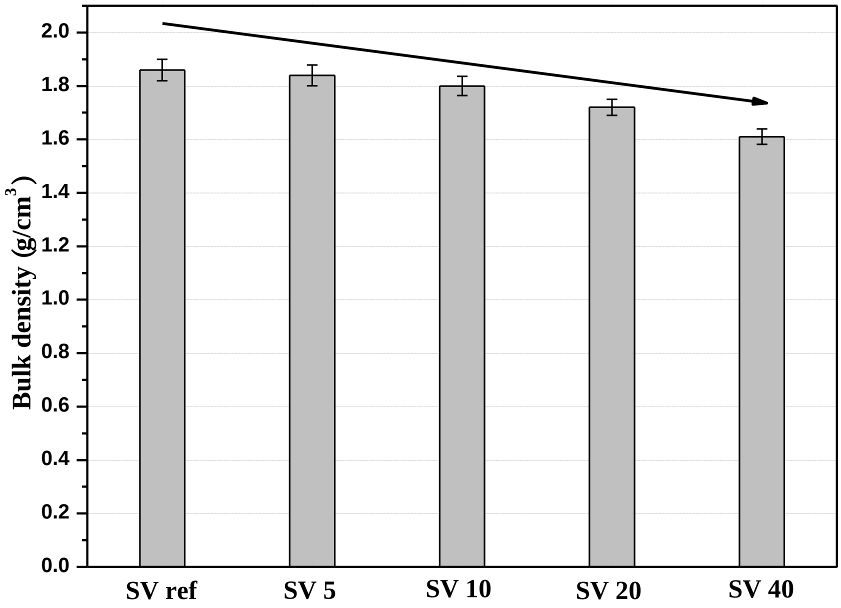


Fig.10 Bulk density of hardened pastes

Fig.11

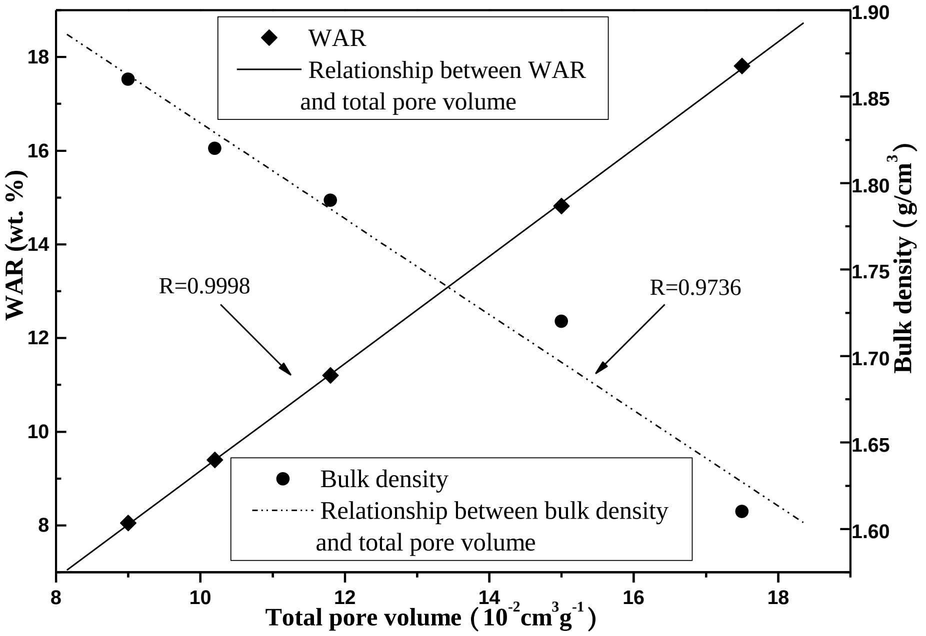


Fig.11 Relationship between total pore volume and WAR, bulk density

Table 1

Table 1 chemical composition of SAC and vermiculite

Component	Amount (wt.%)	
	SAC	Vermiculite
SiO_2	9.16	41.00
CaO	44.37	1.82
Al_2O_3	23.26	15.10
Fe_2O_3	2.53	16.14
MgO	1.59	12.53
K_2O	0.44	5.14
Na_2O	0.29	0.48
TiO_2	1.01	1.91
SO_3	10.11	0.08
Ignition loss	6.24	3.20

Table 2

Table 2 Mix proportions of SAC control sample and samples with additions of vermiculite

No.	Composition (wt. %)	
	SAC	Vermiculite
SV ref	100	0
SV 5	95	5
SV 10	90	10
SV 20	80	20
SV 40	60	40

Table 3

Table 3 WARs of hardened pastes (wt. %)

No.	SV ref	SV 5	SV 10	SV 20	SV 40
WAR	8.05	9.40	11.20	14.82	17.81