Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2014, Article ID 514759, 7 pages
http://dx.doi.org/10.1155/2014/514759

Research Article

Experimental Study of Ultralight (<300 kg/m^3) Foamed Concrete

Xianjun Tan,[1] Weizhong Chen,[1,2] Yingge Hao,[3] and Xu Wang[3]

[1] *State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China*
[2] *Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, Shandong 250061, China*
[3] *Nan-Tun Coal, Zoucheng, Shandong 273515, China*

Correspondence should be addressed to Xianjun Tan; xjtan@139.com

Received 28 April 2014; Revised 25 August 2014; Accepted 26 August 2014; Published 15 October 2014

Academic Editor: Jiangbo Sha

A type of ultralight (<300 kg/m^3) foamed concrete (FC), which can be used as a new energy-conservation and environmental-protection building material and is particularly suitable for the thermal-insulation engineering of building external walls, was produced. The influences of different mixing amounts of fly ash, fly ash activator, WC (WC) ratio, and foaming agent (FA) on the compressive strength of FC were reported. The experimental study indicated that (1) the addition of fly ash reduced the strength of the FC and that the appropriate mixing amount of fly ash in this ultralight FC system should not exceed 45%; (2) with the increasing of fly ash activator, the strength of the FC sample is notably enhanced and the appropriate mixing amount of fly ash activator is 2.5%; (3) the optimized proportion of WC ratio is 0.45, and the FC that was produced according to this proportion has relatively high compressive strength; (4) by increasing the mixing amount of FA, the compressive strength of the FC notably decreases, and the optimal mixing amount of FA in this experiment is 3.5%.

1. Introduction

Foamed concrete (FC) belongs to the broader category of cellular concrete in which air-voids are trapped in the mortar matrix using a suitable aerating agent [1–4]. It is lightweight and has moisture protection, fire protection, sound insulation, and good heat insulation; therefore, it has been successfully applied in oil-well cementing projects, used as a backfill material in excavation projects, and used for sound and heat insulation in building panels, fire-protection wall, energy-absorbing pads in roads, road subbase, structural fill, foundations, and geotechnical and mine fill applications [5–7].

Researchers have successfully produced FC in the density range of 300–1800 kg/m^3 [2–4, 8, 9], as the type of base materials; the foam-producing methods and the properties of FC have been widely studied. Some examples follow.

(i) Constituents of the Base Mixture. In addition to the Ordinary Portland cement, in the rapid-hardening Portland cement, high alumina and calcium sulfoaluminate have been used to reduce the setting time and improve the early strength of the foam concrete. In addition to cement, many types of materials such as silica fume fly ash, lime chalk, crushed concrete, incinerator bottom ash, recycled glass, foundry sand, quarry finer, expanded polystyrene, oil palm shell, and Lytag fines were used to reduce the density of the foam concrete and/or make use of waste/recycled materials [3, 5, 6, 10, 11].

(ii) Methods to Produce Foam. Chemical expansion and mechanical foaming have been used. In chemical foaming, a foaming agent (FA) such as aluminum powder, CaH_2, TiH_2, or MgH_2 is mixed with the base-mix ingredients, and, during the mixing process, foam is produced from the chemical reactions, which forms the cellular structure in the concrete. In mechanical foaming, the foam is prepared in advance using a special device, a foam generator, where the water and chemical admixture are mixed with a certain proportion, and the premanufactured foam is mechanically mixed with the

Table 1: Chemical properties of the cement and the fly ash that were used.

	Cement		Fly ash	
	% by mass	GB175-2007	% by mass	GB/T1596-2005
SiO_2	21.84	—	48.2	—
CaO	65.23	—	19.6	—
Al_2O_3	5.23	—	18.4	—
Fe_2O_3	3.30	—	3.7	—
SO_3	0.98	≤3.5	1.7	≤3.0
MgO	2.76	≤5	1.1	—
$K_2O + Na_2O$	1.6	—	—	—
Loss on ignition	1.5	≤3.0	2.0	≤5.0
Soluble residue	0.19	≤1.5	0.75	—

concrete mixture. After molding, the concrete hardens under normal atmospheric conditions [3, 12, 13].

(iii) Properties of FC. The physical properties (drying shrinkage, density, porosity, air-void system, and sorption), the mechanical properties (compressive strength, tensile strength, modulus of elasticity, and prediction models), the durability, and the functional characteristics (thermal conductivity, acoustical properties, and fire resistance) have been widely discussed [5, 6, 14–19].

Many of the above mentioned studies on FC used cement as one of the main materials. However, cement is a building material with high energy consumption and serious environmental pollution. Therefore, the traditional manufactured FC product contradicts the development mode of green construction materials, although many experimental and theoretical studies were performed by adding a certain amount of industrial waste such as fly ash and slag into the cement; for example, Nambiar and Ramamurthy [10] used fly ash to produce FC with densities of 1000, 1250, and 1500 kg/m^3. Kearsley and Wainwright [5, 6, 17] concluded that the long-term properties of FC could be enhanced by replacing 75% cement with fly ash. Until now, little experimental study was performed on the effect of a high fly ash content on the compressive strength of ultralight (<300 kg/m^3) FC. However, with the scope of FC's applicability getting wider and wider, more and more ultralight (<300 kg/m^3) FC is needed, for example, thermal insulation material for building external walls, backfill material for heat preservation pipes, foundation for the highway roads, and so on. In these applications, the compressive strength demand is not very high; usually 0.3~0.5 MPa will be enough.

In this study, a type of ultralight (<300 kg/m^3) FC was produced, which can be used as a new energy-conservation and environmental-protection building material, and is particularly suitable for the thermal insulation engineering of building external walls. The influences of different mixing amounts of fly ash, fly ash activator, WC ratio, and FA on the compressive strength of FC were reported.

2. Experimental Programs

2.1. Materials

(i) Cement. The cement used in this study was a Chinese standard 425 Portland cement [20]. Its density is 3100 kg/m^3, and its chemical composition is given in Table 1.

(ii) Fly Ash. One-graded ash (pfa) from the Yaomeng power plant in Pingdingshan, China, which was used as dry and screened to remove some large particles. The number of particles with a diameter larger than 45 mm was controlled to be less than 12.5%. Its technical performance was consistent with the result recorded in "fly ash used in cement and concrete" GB/T1596-2005 [21], and the chemical composition is shown in Table 1.

(iii) Foaming Agent (FA). It has 27.5% concentration of hydrogen peroxide; it reacts with the catalyst (MnO_2) to form oxygen gas during the making process of FC. The reaction equation is as follows:

$$2H_2O_2 \xrightarrow{MnO_2} 2H_2O + O_2 \uparrow \tag{1}$$

(iv) Foam Stabilizer. It is a self-made, white powder. It is made of triethanolamine (20%), polyacrylamide (40%), and hydroxypropyl methyl cellulose (40%), its mixing amount is 1% of FA, and its main function is to improve the slurry viscosity.

(v) Fly Ash Activator. It is self-made; the main component is CaO white powder (80%), with the other components including NaOH (8%) and Na_2SO_4 (12%). The activation principle of CaO is as follows: the chemical activity of fly ash is from soluble SiO_2 and Al_2O_3 in the vitreous body, and they can react with CaO in the presence of water, generating

hydrated calcium silicate, and after that the strength will come into being. The reaction equations are as follows:

$$\mathrm{CaO} + \mathrm{H_2O} = \mathrm{Ca(OH)_2} \tag{2}$$

$$\mathrm{m_1Ca(OH)_2} + \mathrm{SiO_2} + \mathrm{nH_2O} \longrightarrow \mathrm{m_1CaO} \cdot \mathrm{SiO_2} \cdot \mathrm{nH_2O} \tag{3}$$

$$\mathrm{m_1Ca(OH)_2} + \mathrm{Al_2O_3} + \mathrm{nH_2O} \longrightarrow \mathrm{m_1CaO} \cdot \mathrm{Al_2O_3} \cdot \mathrm{nH_2O} \tag{4}$$

The function of NaOH is to make the solution into alkaline environment, which can provide the basis for the ash reaction. $\mathrm{OH^-}$ will prompt Si–O, Al–O bond to rupture and this will accelerate the hydration speed. The function of $\mathrm{Na_2SO_4}$ is mainly to accelerate the speed and promote the level of activation of fly ash excitation. This is because $\mathrm{SO_4}^{2-}$ can react with $\mathrm{AlO^{2-}}$ when $\mathrm{Ca^{2+}}$ exists, generating hydrated calcium aluminate. It can cover the fly ash particles and form a fibrous layer, and the close degree is smaller than C–S–H, which is more beneficial to $\mathrm{Ca^{2+}}$ diffusing into the fly ash particles.

(vi) Catalyst. It is a manganese dioxide ($\mathrm{MnO_2}$) powder; its molecular weight is 86.94 (g/mol).

2.2. Test Equipment

(i) A high-speed blender: autocontrol with a rotating speed of 0~1200 r/min.

(ii) A standard tester for consistency and setting time of the cement *(Vicat Apparatus)*.

(iii) A funnel of cement mortar consistency: produced by Hebei Guanghua Weiye Construction Instrument Factory, with a capacity of 1725 mL.

(iv) Multifunction rock mechanics test (RMT) machine: a series of RMT systems was developed at our institute. The machine has a unique multifunction design and control technology; it can conduct many types of tests such as uniaxial compression, triaxial compression, tension, shear, and fatigue tests. Its maximum load is 1 MN, and its maximum confining pressure is 50 MPa.

(v) An electrothermal blowing drying oven with the type of OL-103.

(vi) Constant-temperature-and-humidity curing box: Beijing Huachuang Northern Experimental Apparatus Co., Ltd.

2.3. Preparation of FC

(i) Add water into other materials such as cement, fly ash, foam stabilizer, and fly ash activator except FA and evenly stir while maintaining the temperature of the slurry at approximately 45°C. In general, this process lasts approximately 5 minutes.

(ii) While stirring at high speed, quickly add FA and continue stirring for approximately 30 seconds.

(iii) Pour the evenly stirred slurry into a 1200 mm × 900 mm × 350 mm mold and wait until it foams; the foam process is shown in Figure 1.

(iv) Take apart the mold after 2 hours and keep it in the curing box with constant temperature and humidity until the test age ends. Use a 100 mm × 100 mm × 100 mm sample to perform the test; the pore structure is shown in Figure 2.

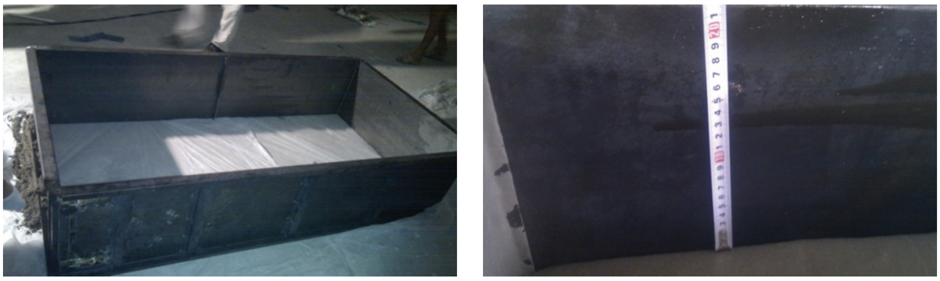
The entire FC preparation process using chemical foaming can be summarized as a dynamic balance process. The design process of the experiment must carefully consider the denseness of the slurry, the foaming speed, the condensation speed of the slurry, the additive amount of FA, and other influencing factors to prepare a relatively high-quality product. The key to FC structure formation using chemical foaming is to make the foaming speed match the setting and hardening speed of the slurry.

3. Results and Discussion

3.1. The Influence of the Mixing Amount of Fly Ash on the Compressive Strength. The strength of the FC is directly related to the proportion of the gelled material. Larger proportions of the concrete in the gelled material correspond to higher strengths of the product. In the cement-fly ash system, the massive use of fly ash will dramatically reduce the strength of the concrete, which is particularly obvious in the ultralight FC that is based on cement-fly ash [5, 6, 18]. Therefore, the amount of fly ash is greatly limited in ultralight FC products. Nevertheless, a moderate amount of fly ash activator can effectively improve the early strength of the products [22], which is also beneficial to shorten the stripping time of the products and improve the production efficiency. For the FC with a fixed fly-ash-activator mixing amount of 2.5% and a dry bulk density of 290 kg/m^3, the strength of 28 d products decreases as the fly ash content increases, as shown in Figure 3.

When the fly ash content is smaller than 45%, the downtrend of the product strength is moderate: when the mixing amount changed from 30% to 45%, the strength decreased by 0.14 MPa. However, when the fly ash content is larger than 45%, the downtrend of the product strength is intensified: when the mixing amount changed from 45% to 55%, the strength decreased by 0.37 MPa, and the product strength was only 0.15 MPa when the fly ash content was 55%. Therefore, for practicability, the appropriate mixing amount of fly ash in this ultralight FC system should not exceed 45%.

3.2. The Influence of the Mixing Amount of Fly Ash Activator on the Compressive Strength. FC strength is directly related to the proportion of cement in the cementitious materials, and many researchers have studied the activation of the reactivity of natural pozzolans and fly ashes [22–25]. In this study, the fly ash activator is self-made, and its main component is CaO. The activation mechanism of fly ash by CaO can be explained as follows. The substance in lime that ultimately affects the activity of the fly ash is $\mathrm{Ca(OH)_2}$; $\mathrm{Ca(OH)_2}$ can



(a) Before pouring the slurry (b) 0 min

(c) 1 min (d) 2 min

(e) 3 min (f) 4 min

Figure 1: The foam process of FC.

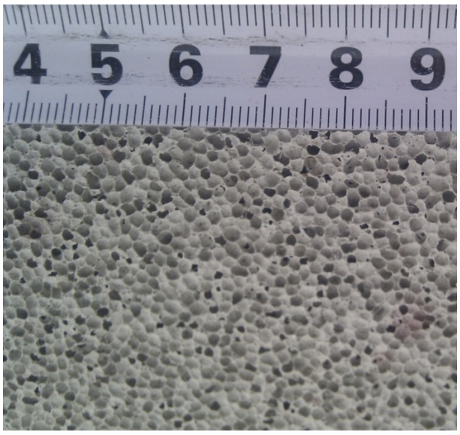


Figure 2: The pore structure of FC.

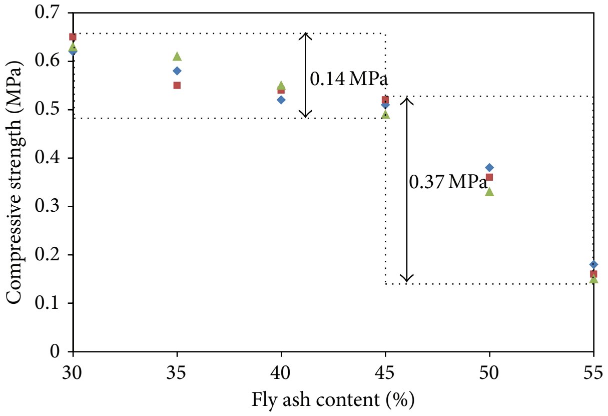


Figure 3: The influence of fly ash content on the compressive strength of FC.

provide OH^- to unfold the chemical bonds between Si–O and Al–O and Ca^{2+} to generate the hydraulic cementing materials by the hydration of fly ash. However, the reaction must have a moderate amount of sulfate to rapidly, fully, and economically activate the fly ash at normal temperature and pressure. Therefore, the mixing amount of self-made fly ash activator is critical to activating the strength of fly ash.

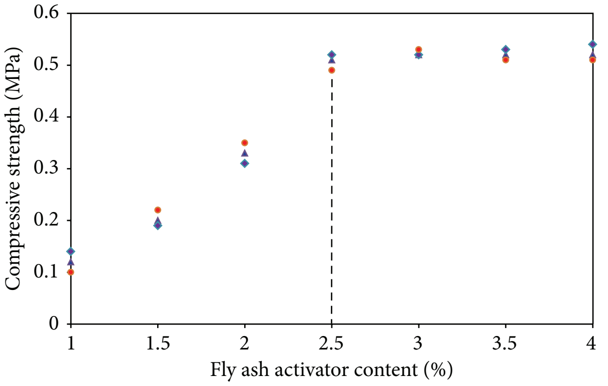


Figure 4: The influence of fly ash activator content on the compressive strength of FC.

The influence of the mixing amount of fly ash activator on the compressive strength of FC, which has a fixed internally doped fly ash content of 45% and a dry bulk density of 290 kg/m^3, is shown in Figure 4. As shown in Figure 4, the strength of FC sample is notably enhanced with the increase in the amount of fly ash activator. When the mixing amount of fly ash activator is more than 2.5%, the strength increase of FC tends to level off, which implies that the mixing amount of fly ash activator has an optimum value. In this ultralight FC system, the appropriate mixing amount of fly ash activator is 2.5%.

3.3. The Influence of WC Ratio on the Compressive Strength. The WC ratio is another important factor that can influence the performance of FC [5, 6]. In the preparation of FC by chemical foaming, the thickening speed and the foaming speed of the slurry must highly match, which indicates that the foaming and the static maintenance of the slurry are synchronized. In the preparation process of FC, the WC ratio significantly influences the entire preparation technology: when the WC ratio is excessively low and the slurry is too thick, it opposes the full dispersion of FA and leads to partially intensified foaming and large blowholes; besides, the initial setting time of the slurry is notably short if the WC ratio is low. If the slurry sets before the foaming procedure of FA finishes, the products will become overstressed inside and flaws will appear. When the WC ratio is excessively large and the denseness of the slurry is excessively low, the condensation and stiffening of the slurry lag behind the foaming of FA, which will cause the FC to collapse in the later stage. The influence of the WC ratio on the compressive strength of FC is shown in Figure 5. When the WC ratio increases from 0.40 to 0.50, the compressive strength of the sample first increases and later decreases because in this range of WC ratio, the consistency of the slurry is moderate, and the gases evenly scatter in the slurry; thus, FA is fully foamed, and the volume of the slurry steadily enlarges. Meanwhile, the pore structure is well set because the initial setting speed of the slurry matches the foaming speed of FA. Thus, the compressive strength of the sample is relatively high. When the WC ratio increases from 0.45 to 0.50, the denseness of the slurry is too low, and it is extremely easy for the gas to rush out of the surface of the sample and leave cracks and through holes in the sample, which will decrease the strength of the sample. In addition, because the WC ratio is too large, the coagulation time is longer than the vesicant's foaming time; in the later foaming stage, parts of the pores merge, which decreases the evenness and significantly decreases the strength of the pore structure in the sample. Therefore, in the experiment, the optimal WC ratio is 0.45. The FC that was produced with this WC ratio has a relatively high compressive strength.

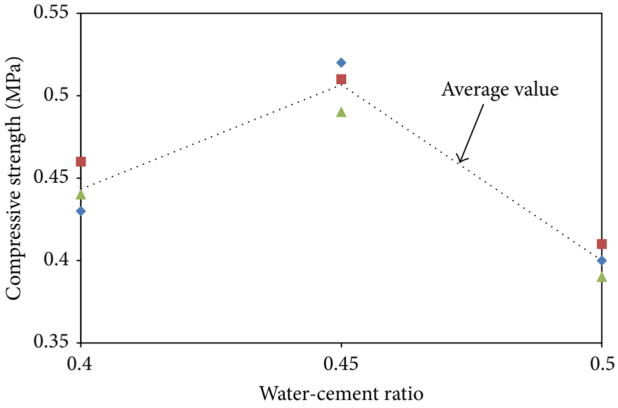


Figure 5: The influence of the WC ratio on the compressive strength of FC.

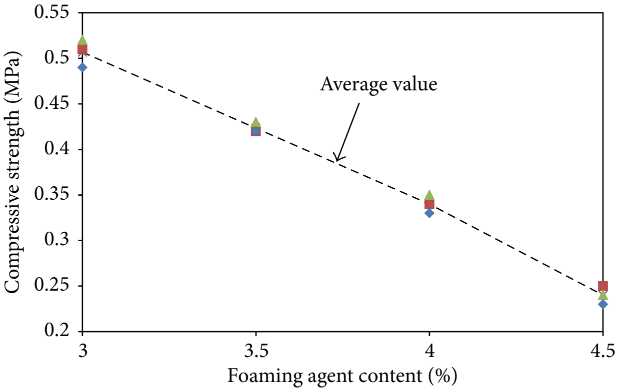


Figure 6: The influence of the FA content on the compressive strength of FC.

3.4. The Influence of FA on the Compressive Strength. FA is one of the basic raw materials to prepare FC. FA generates chemical reactions in the evenly stirred slurry, which create a lot of gas. The gas scatters inside the slurry and is gradually fixed in the hardened concretes as the slurry condenses; finally, the gas forms the even and stable vesicular structure. Figure 6 shows the influence of the amount of FA mixture on the 28-day compressive strength of FC. From Figure 6, it can be observed that the compressive strength of the FC decreases as the amount of FA mixture increases because the amount of air holes inside the FC also increases and the walls of the air holes become thinner. Therefore, the dry bulk density of FC decreases, and so does the strength. It is observed that the pore wall of the sample with the H_2O_2 admixture amount of 3% is the thickest with almost no interlocking pores; thus, this sample has the maximum compressive strength. The pore wall of the sample with the H_2O_2 mixing amount of 4.5% is the thinnest with many interlocking pores; thus, it has the minimum strength. For the sample that was made using the FA with the H_2O_2 admixture amount of 3.5%, the pore wall thickness and the pore structures are relatively appropriate, and the strength is also qualified with the heat-preservation requirement of the exterior wall. Therefore, the optimal amount of FA admixture in this experiment is 3.5%.

4. Conclusions

A type of ultralight (<300 kg/m^3) FC was produced. The influences of various mixing amounts of fly ash, fly ash activator, WC ratio, and FA on the compressive strength of FC were experimentally studied and can be summarized as follows.

(1) The denseness of the slurry, the foaming speed, the condensation speed of the slurry, the additive amount of FA, and other influencing factors must be carefully conblacksidered to prepare a relatively high-quality product. In the formation of FC structures using chemical foaming, the foaming speed must match the setting and hardening speed of the slurry.

(2) When the fly ash content is smaller than 45%, the product strength moderately decreases, whereas when the fly ash content is larger than 45%, the product strength rapidly decreases. For practicability, the appropriate mixing amount of fly ash in this ultralight FC system should not exceed 45%.

(3) With the increase in the amount of fly ash activator, the strength of the FC sample is notably enhanced. When the mixing amount of fly ash activator is more than 2.5%, the strength increase of FC tends to level off. In this ultralight FC system, the appropriate mixing amount of fly ash activator is 2.5%.

(4) In the experiment, the optimized proportion of WC is a ratio of 0.45. The FC that was produced with this proportion has a relatively high compressive strength.

(5) With the increase of the amount of FA admixture, the compressive strength of the FC notably decreases. The pore wall thickness and the pore structures of the sample that was produced using the FA with the H_2O_2 admixture amount of 3.5% are relatively appropriate, and the strength also satisfies the heat-preservation requirement of the exterior wall. Therefore, the optimal amount of FA admixture in this experiment is 3.5%.

Conflict of Interests

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

Acknowledgments

This work was supported by the National Program on Key Basic Research Project (973 Program) (Grant no. 2013CB036006), the National Natural Science Foundation of China (Grant nos. 51208499, 41102193, and 51109207), the Postdoctoral Science Foundation of China (2014M550365), and the National Science Fund for Distinguished Young Scholars of China (Grant no. 51225902).

References

[1] N. Narayanan and K. Ramamurthy, “Microstructural investigations on aerated concrete,” *Cement and Concrete Research*, vol. 30, no. 3, pp. 457–464, 2000.

[2] N. Narayanan and K. Ramamurthy, “Structure and properties of aerated concrete: a review,” *Cement and Concrete Composites*, vol. 22, no. 5, pp. 321–329, 2000.

[3] K. Ramamurthy, E. K. K. Nambiar, and G. I. S. Ranjani, “A classification of studies on properties of foam concrete,” *Cement and Concrete Composites*, vol. 31, no. 6, pp. 388–396, 2009.

[4] U. J. Alengaram, B. A. Al Muhit, M. Z. bin Jumaat, and M. L. Y. Jing, “A comparison of the thermal conductivity of oil palm shell foamed concrete with conventional materials,” *Materials and Design*, vol. 51, pp. 522–529, 2013.

[5] E. P. Kearsley and P. J. Wainwright, “The effect of high fly ash content on the compressive strength of foamed concrete,” *Cement and Concrete Research*, vol. 31, no. 1, pp. 105–112, 2001.

[6] E. P. Kearsley and P. J. Wainwright, “Porosity and permeability of foamed concrete,” *Cement and Concrete Research*, vol. 31, no. 5, pp. 805–812, 2001.

[7] M. A. O. Mydin and Y. C. Wang, “Mechanical properties of foamed concrete exposed to high temperatures,” *Construction and Building Materials*, vol. 26, no. 1, pp. 638–654, 2012.

[8] L. de Rose and J. Morris, “The influence of mix design on the properties of micro-cellular concrete,” in *Specialist Techniques and Materials for Construction*, R. K. Dhir and N. A. Handerson, Eds., pp. 185–197, Thomas Telford, London, UK, 1999.

[9] M. Turner, “Fast set foamed concrete for same day reinstatement of openings in highways,” in *Proceedings of the One Day Seminar on Foamed Concrete: Properties, Applications and Latest Technological Developments*, pp. 12–18, 2001.

[10] E. K. K. Nambiar and K. Ramamurthy, “Influence of filler type on the properties of foam concrete,” *Cement and Concrete Research*, vol. 28, pp. 475–480, 2006.

[11] U. J. Alengaram, H. Mahmud, and M. Z. Jumaat, “Comparison of mechanical and bond properties of oil palm kernel shell concrete with normal weight concrete,” *International Journal of Physical Sciences*, vol. 5, no. 8, pp. 1231–1239, 2010.

[12] A. Laukaitis, R. Žurauskas, and J. Keriene, “The effect of foam polystyrene granules on cement composite properties,” *Cement and Concrete Composites*, vol. 27, no. 1, pp. 41–47, 2005.

[13] S. B. Park, E. S. Yoon, and B. I. Lee, “Effects of processing and materials variations on mechanical properties of lightweight cement composites,” *Cement and Concrete Research*, vol. 29, no. 2, pp. 193–200, 1999.

[14] Y. M. Hunaiti, “Composite action of foamed and lightweight aggregate concrete,” *Journal of Materials in Civil Engineering*, vol. 8, no. 3, pp. 111–113, 1996.

[15] Y. M. Hunaiti, “Strength of composite sections with foamed and lightweight aggregate concrete,” *Journal of Materials in Civil Engineering*, vol. 9, no. 2, pp. 58–61, 1997.

[16] C. T. Tam, T. Y. Lim, R. Sri Ravindrarajah, and S. L. Lee, “Relation between strength and volumetric composition of moist-cured cellular concrete,” *Magazine of Concrete Research*, vol. 39, no. 138, pp. 12–18, 1987.

[17] E. P. Kearsley and P. J. Wainwright, “Ash content for optimum strength of foamed concrete,” *Cement and Concrete Research*, vol. 32, no. 2, pp. 241–246, 2002.

[18] E. P. Kearsley and P. J. Wainwright, “The effect of porosity on the strength of foamed concrete,” *Cement and Concrete Research*, vol. 32, no. 2, pp. 233–239, 2002.

[19] X. J. Tan, W. Z. Chen, H. M. Tian, and J. P. Yuan, “Degradation characteristics of foamed concrete with lightweight aggregate and polypropylene fibre under freeze-thaw cycles,” *Magazine of Concrete Research*, vol. 65, no. 12, pp. 720–730, 2013.

[20] GB175-2007, “Portland cement and ordinary portland cement,” National Standard of the People’s Republic of China, 2007, (Chinese).

[21] GB/T1596-2005, *Fly Ash Used in Portland Cement and Concrete*, National Standard of the People’s Republic of China, Beijing, China, 2005.

[22] C. J. Shi, “Pozzolanic reaction and microstructure of chemical activated lime-fly ash pastes,” *ACI Materials Journal*, vol. 95, no. 5, pp. 537–545, 1998.

[23] J. S. Qian, C. J. Shi, and Z. Wang, “Activation of blended cements containing fly ash,” *Cement and Concrete Research*, vol. 31, no. 8, pp. 1121–1127, 2001.

[24] C. Shi and R. L. Day, “Acceleration of the reactivity of fly ash by chemical activation,” *Cement and Concrete Research*, vol. 25, no. 1, pp. 15–21, 1995.

[25] R. L. Day and C. Shi, “Influence of the fineness of pozzolan on the strength of lime natural-pozzolan cement pastes,” *Cement and Concrete Research*, vol. 24, no. 8, pp. 1485–1491, 1994.

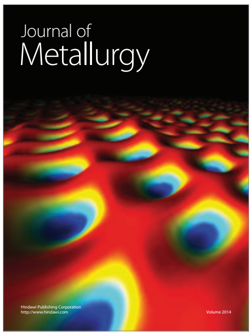

Journal of Nanotechnology

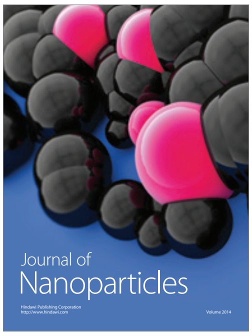
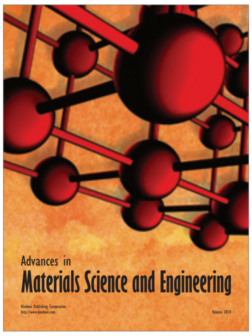
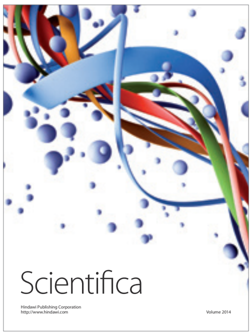
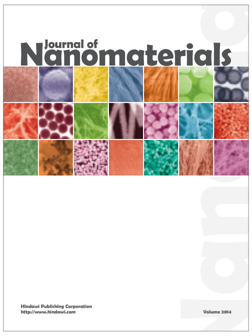
International Journal of Corrosion

International Journal of Polymer Science

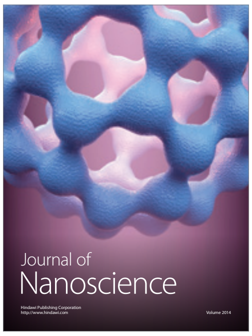
Smart Materials Research

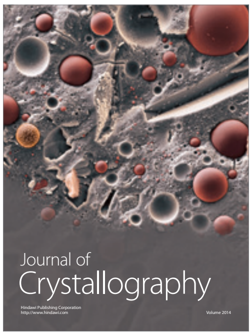
Journal of Composites

BioMed Research International

Journal of Metallurgy


Journal of Materials

Journal of Nanoparticles

Advances in Materials Science and Engineering

Scientifica

Journal of Nanomaterials

The Scientific World Journal

International Journal of Biomaterials

Journal of Nanoscience

Journal of Coatings

Journal of Crystallography

Journal of Ceramics

Journal of Textiles