Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cement & Concrete Composites 28 (2006) 520–527

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete

Daneti Saradhi Babu [a,*], K. Ganesh Babu [b], Wee Tiong-Huan [a]

[a] Department of Civil Engineering, National University of Singapore, Blk. E1A-07-03, 1 Engineering Drive 2, Singapore 117576, Singapore
[b] Department of Ocean Engineering, Structures and Materials Laboratory, Indian Institute of Technology Madras, Chennai 600036, India

Received 31 March 2005; accepted 24 February 2006

Abstract

The aim of this study is to investigate the effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete. The present study covers the use of expanded polystyrene (EPS) and un-expanded polystyrene (UEPS) beads as lightweight aggregate in concretes that contain fly ash as a supplementary cementitious material. Lightweight concrete with wide range of concrete densities (1000–1900 kg/m^3) were studied mainly for compressive strength, split tensile strength, moisture migration and absorption. The results indicate that for comparable aggregate size and concrete density, concrete with UEPS aggregate exhibited 70% higher compressive strength than EPS aggregate. EPS aggregate concrete with small EPS aggregates showed higher compressive strength and the increase in compressive strength was more pronounced in low density concrete when compared with high density concrete. The UEPS aggregate concrete exhibited brittle failure similar to normal weight concrete (NWC), whereas, gradual failure was observed in EPS concrete. Moreover, the moisture migration and absorption results indicate that the EPS concrete containing bigger size and higher volumes of EPS aggregate show higher moisture migration and absorption.

Keywords: Expanded polystyrene; Fly ash; Compressive strength; Splitting tensile strength; Moisture migration; Water absorption

1. Introduction

The uses of lightweight concrete has been increasing especially in the construction of high rise buildings, offshore structures and long span bridges due to the advantage of its low density, which results in a significant benefit in terms of load bearing elements of smaller cross section and a corresponding reduction in the size of the foundation [1]. The lightweight concrete can be produced by introducing: 1. gassing agents such as aluminum powder or foaming agents, 2. lightweight mineral aggregate such as perlite, vermiculite, pumice, expanded shale, slate, clay, etc., 3. plastic granules as aggregate e.g. polystyrene or other polymer materials [2]. The low density lightweight concretes made with first two methods absorb high amounts of water (20–50% weight of dry concrete), which increase the weight of floating structure [3,4]. The weight of the structure is an important factor particularly in the design of floating marine structures. Lightweight concrete made with non-absorbent, artificial ultra-lightweight (density of less than 300 kg/m^3) EPS aggregate can be used to produce a lightweight concrete that floats on water [2,5].

Polystyrene concrete is made from a mixture of cement, sand and polystyrene aggregate (EPS or UEPS aggregates). Polystyrene is a thermoplastic polymeric material initially in the solid form (UEPS) and it can be expanded by the use of steam and expansive agents [6]. EPS aggregates are commercially available worldwide, unlike the other artificial lightweight aggregates (expanded clay, shale, slate, sintered pfa, etc.), where most of the production plants are concentrated in Russia and Europe [5]. EPS aggregate has a closed cell structure consisting essentially of 98% air [1]. By incorporating the polystyrene aggregate at different

* Corresponding author. Tel.: +65 6874 1312.
E-mail address: saradhibabu@nus.edu.sg (D.S. Babu).

0958-9465/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2006.02.018

volumes in the concrete, mortar or in the cement paste, a wide range of concrete densities can be produced.

Polystyrene aggregate can be used to produce low density concretes required for building applications [6] and it can be used for other specialised applications like the sub-base material for pavement and railway track bed, as construction material for floating marine structures, sea beds and sea fences, as an energy absorbing material for the protection of buried military structures and as fenders in offshore oil platforms [5,7–10]. Moreover, for equal concrete densities, EPS aggregate concrete have exhibited 70–270% higher compressive strength than vermiculite or perlite aggregate concrete [11] and these were found to be fire-resistant and hence used as a good thermal insulation material in building construction [2,11].

In recent years, the construction industry has been widely using fly ash with cement and this reflected in various changes in the standards worldwide. Moreover, it is known that the use of fly ash in NWC has shown excellent mechanical properties and long-term durability [12–14]. However, the information on the use of fly ash as supplementary cementitious material in lightweight polystyrene concrete is still meager.

This is the fourth in a series of reports on the comprehensive results of an investigation on the behaviour of lightweight concretes containing polystyrene aggregates and mineral admixtures. The first paper reported the strength and durability of EPS concrete containing silica fume [15], the second on the durability and corrosion performance [16] and the third on the strength behaviour of EPS concrete containing 50% fly ash [17]. The main objective of this work is to study the effect of polystyrene aggregate size on strength and moisture migration characteristics of polystyrene concrete containing fly ash.

2. Experimental investigation

2.1. Materials and mix proportions

Ordinary Portland cement (OPC) conforming to both IS:12269 and ASTM Type I, Class F fly ash and silica fume were used as cementitious materials in the concrete mixes. The chemical characteristics of cement, fly ash and silica fume are given in Table 1. Sand finer than 2.36 mm, and with a fineness modulus of 2.8, was used. Normal coarse aggregate (crushed blue granite) passing through 8 mm sieve was used in concrete of higher density. Commercially available spherical shaped polystyrene aggregates of different sizes labeled as P, Q and U, were used. Types P and U have same aggregate grading, however, the Type P is EPS aggregate and the Type U is UEPS aggregate. The properties and grading details of polystyrene aggregates are given in Table 2. All the polystyrene concretes were initially designed as per the recommendations of ACI-211.2 [18] and were modified by considering the efficiency of fly ash, similar to the mixes designed for previous studies [15–17,19]. The detailed mix proportions are given in Table 3. The production and curing of concrete adopted has been described earlier [15–17].

Table 1
Chemical composition of the cement, fly ash and silica fume

Chemical composition	OPC	Fly ash	Silica fume
Silica (SiO_2)	21.78	58.29	74.07
Alumina (Al_2O_3)	6.56	31.74	2.22
Ferric oxide (Fe_2O_3)	4.13	5.86	1.57
Calcium oxide (CaO)	60.12	1.97	2.95
Magnesium oxide (MgO)	2.08	0.14	1.27
Sodium oxide (Na_2O)	0.36	0.76	2.89
Potassium oxide (K_2O)	0.42	0.76	6.51
Sulphuric anhydride (SO_3)	2.16	0.15	0.95
Loss on ignition (LOI)	2.39	0.31	7.67

Table 2
Characteristics of polystyrene aggregates

Sieve size (mm)	Grading of polystyrene aggregate – cumulative passing (%)[a]		
	Type P	Type Q	Type U
8	100	100	100
6.3	100	100	100
4.75	100	0	100
2.36	100	0	100
1.18	0	0	0
Bulk density (kg/m^3)	23.6	9	66.5
Specific gravity	0.029	0.014	1.02

[a] Types P and Q are EPS; Type U is UEPS.

2.2. Test program

The flow values of the fresh concrete were measured according to ASTM C 124-1973. Compressive strength tests were carried out on 100 mm cubes at the age of 1, 3, 7, 28 and 90 days on a testing machine of 2000 kN capacity at a loading rate of 2.5 kN/s. The splitting tensile strength test was conducted on cylinders of 100 mm in diameter and 200 mm in height, at 28 days as per ASTM C 496-89. Each of the results reported for the compressive strength and splitting tensile strength were average results of two specimens. However, if the variation between the two values is more than 10%, an additional specimen was tested to find this average.

The moisture migration test was carried out on different polystyrene concrete in order to characterize the rate of moisture migration of water into the pores in concrete. After 28 days of curing, two 100 mm cube specimens were properly cleaned with nylon brush and washed thoroughly with flowing water. These specimens were dried in a similar manner to the specimens prepared earlier for absorption study [15,16]. The schematic diagram of the moisture migration test setup used is shown in Fig. 1. All the dried specimens in this test were placed on cotton cloth, which rests on perforated steel plate. The test was carried out up to the point at which the difference between two

Table 3
Mix details of the concretes investigated

Name	Cement (kg/m^3)	Fly ash (kg/m^3)	w/(c+f) ratio	Weight distribution of aggregate[a]			% Volume of PS in total	SP% of TCM[b]	Wet density (kg/m^3)	Flow (mm)
				Sand (%)	CA (%)	PS (%)				
Series I: EPS concretes containing 30% fly ash										
P105	394	169	0.355	15	–	85	50	0.50	1012	605
P143	394	169	0.355	14	26	60	35	0.50	1492	630
P182	394	169	0.355	24	42	34	20	0.50	1858	590
Q105	394	169	0.355	15	–	85	50	0.50	1076	580
Q143	394	169	0.355	14	26	60	35	0.50	1454	550
Q182	394	169	0.355	24	42	34	20	0.50	1842	490
NWC	525	–	0.378	33	67	0	0	–	2410	–
Series II: UEPS concretes[c]										
UF175	393	212	0.265	18	31	51	30	1.00	1786	520
US175	454	51	0.327	20	34	46	30	1.25	1795	550

[a] CA – normal coarse aggregate; PS – polystyrene aggregate (EPS or UEPS).
[b] TCM – total cementitious material.
[c] UF175 – designed with 35% fly ash replacement and US175 – designed with 10% silica fume replacement.

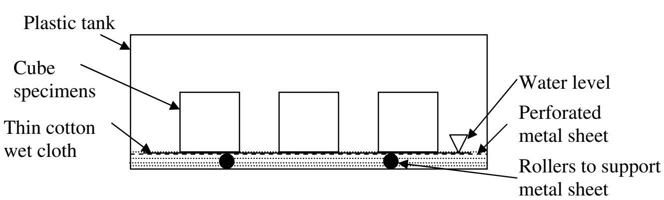

Fig. 1. Diagrammatic representation of moisture migration test setup.

consecutive readings at 12 h interval was almost negligible. The absorption test was also carried out to verify the results of moisture migration test. The weight gains were measured in both the tests.

3. Results and discussion

3.1. Compressive strength

The variation of compressive strength with age for different size of polystyrene aggregates is shown in Fig. 2. It can be observed that for similar concrete densities, the strength of concretes increases with decrease in the size of EPS aggregate and this is in accordance with a recent study [20]. This increase is consistent for all the concrete densities (1050, 1430 and 1820 kg/m^3). The increase in compressive strength of the EPS concretes observed at 28 days and 90 days in 1050, 1430 and 1820 kg/m^3 density are 27% and 39%, 14% and 9% and 11% and 5% respectively, with the use of smaller size (P) instead of bigger size (Q) EPS aggregate. It indicates that the increase of compressive strength with decrease in EPS aggregate size was significant in lower density concrete. This may be due to the fact that the lower density concrete generally have high amount of EPS, inherently has lower strength; therefore the benefit obtained with the use of small size aggregate was significant. Whereas, in case of higher density concrete, contain lower amount of EPS aggregate usually have higher strength, therefore the strength contribution due to the use of small size aggregate may be not significant.

The Types P and U have same aggregate size, however, the concrete containing UEPS (Type U) aggregate showed about 70% higher compressive strength than concrete with EPS aggregate (Type P) for comparable water to binder ratio and concrete density. Lower compressive strength in EPS concrete may be due to the difference in the density of aggregates i.e., EPS has 60% lower density than UEPS aggregate (Table 2).

While testing for compressive strength, the concrete containing EPS and UEPS aggregate showed different behaviour. In the case of EPS concrete, the failure mode of concrete specimens under compressive loading did not exhibit the typical brittle failure normally associated with NWC. The failure observed was more gradual (compressible), and the specimens were capable of retaining the load after failure without full disintegration [15,17,21]. Whereas, a typical brittle failure was observed in concretes containing UEPS aggregate. It was also noticed that EPS aggregates sheared off along the failure plane in EPS concrete, whereas, in UEPS concrete, no damage to the UEPS aggregate was observed. However it was observed that some of the UEPS aggregate along the failure plane was de-bonded from the matrix. This indicates that the bond between UEPS aggregate and the matrix is weaker than the failure strength of the UEPS aggregate. The bond between the EPS aggregate and the matrix seems to be stronger than the failure strength of the EPS aggregate. The recent micro-structural study on EPS aggregate concrete also suggests the strong interfacial bond with EPS aggregate [22].

The variation of compressive strength with age (Fig. 2) shows a continuous increase in all the mixes. It is to be noted that the EPS concretes containing 30% fly ash have shown 70% of 28-day compressive strength in 7 days. In contrast, the strength gain of almost 95% of the 28-day strength in 7 days was reported in EPS concretes made with OPC [6]. The lower rate of strength gain in concretes

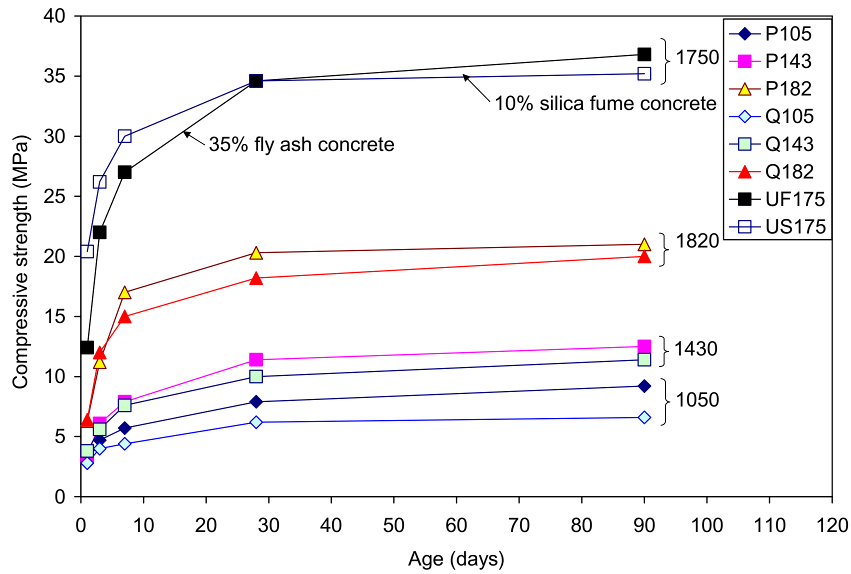

Fig. 2. Variation of compressive strength with age for different densities.

containing fly ash may be due the effect of slow reactivity of fly ash at early ages [23]. For the same replacement of silica fume (Fig. 2), UEPS concrete shows about 85% of 28-day strength in 7 days, in contrast to the EPS concretes shows 95% of 28-day strength in 7 days [16]. It shows that strength development with EPS aggregate seems to be higher than that with UEPS aggregates. This may be due to the high heat of hydrations in EPS aggregate concrete, which may take place due to the significant increase of thermal resistivity and decrease of specific thermal capacity of concrete with EPS aggregate [6].

Density is one of the important parameters which can control many physical properties in lightweight concrete and it is mainly controlled by the amount and density of lightweight aggregate. The previous studies indicate that the density of EPS concrete decreases with increase in volume of EPS aggregate and hence results in a decrease in compressive strength of the concrete [15,17]. The relationship between compressive strength and fresh concrete density of EPS aggregate concrete is shown in Fig. 3. The figure also shows the strength and density results of EPS aggregate concrete from different sources [4,6,9,15,17,24]. The relationship between fresh concrete density and compressive strength ($r = 0.976$) based on the results of 60 EPS concretes with densities ranging from 200 to 2000 kg/m^3 can be proposed as

$$f_c = 10.3 * \gamma^{1.918} * 10^{-6} \tag{1}$$

where f_c is the compressive strength (MPa) and γ is the fresh concrete density (kg/m^3) of the concrete.

3.2. Splitting tensile strength

Similar to compressive strength, the splitting tensile strength of EPS aggregate concrete also increased with decrease in EPS aggregate size. While testing for splitting tensile strength, the failure mode of concrete specimen containing EPS aggregate also did not exhibit the typical brittle failure normally observed in NWC. The failure observed was more gradual and the specimens did not separate into two pieces in concrete containing EPS volumes of 35% and 50%. This gradual failure was more significant in concrete made with high EPS volumes. Similar type of failure was also reported earlier for the concretes containing plastic shredded aggregate [21,25]. However, the concrete containing UEPS aggregate exhibited a similar failure as NWC.

The relationship between splitting tensile strength and compressive strength (Fig. 4) indicates increase in splitting tensile strength with an increase in compressive strength. The figure also shows higher tensile strength in concrete containing 30% fly ash as compared to silica fume concrete [16]. This may be due to the fact that 30% fly ash concretes were designed with lower water to binder ratios than 50% fly ash and silica fume concretes [16,17]. The relationship between splitting tensile strength and compressive strengths of 40 EPS aggregate concretes made with different binder types exhibited good correlation ($r = 0.947$) for the compressive strengths ranging from 3 to 22 MPa. The relationship can be proposed as

$$f_{ct} = 0.2416 * f_c^{0.7933} \tag{2}$$

where f_{ct} is the splitting tensile strength (MPa) and f_c is the compressive strength (MPa) of EPS concrete.

3.3. Moisture migration

The durability of concrete primarily depends upon its permeability, which defines the resistance to the ingress of aggressive ions. The moisture migration and absorption characteristics indirectly represent the porosity through an understanding of the permeable pore volume and its connectivity. Concretes with greater porosity results in higher

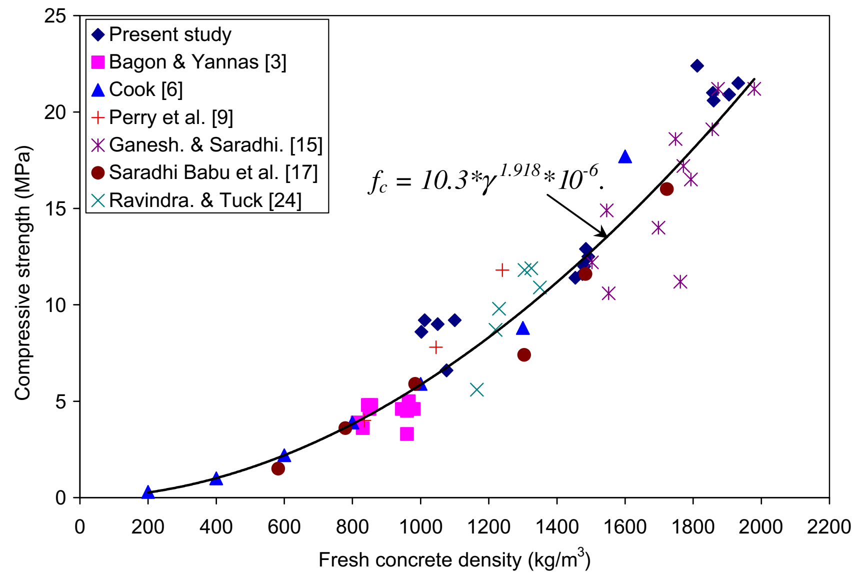

Fig. 3. Relationship between compressive strength and fresh concrete density.

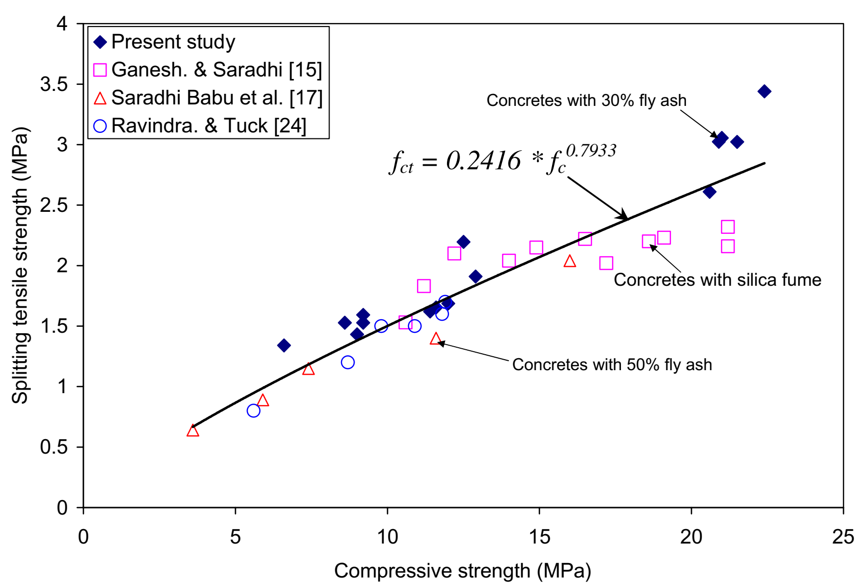

Fig. 4. Relationship between splitting tensile strength and compressive strength.

moisture migration, which indicate higher weight gains. The variation of moisture migration with time for both EPS and UEPS aggregate concretes are shown in Fig. 5. Though all these concretes have the same water to binder ratio and binder content, the moisture migration was observed to be different for EPS concretes made with different sizes of EPS aggregate (Types P and Q) and different EPS aggregate volumes (20%, 35% and 50%).

For the same size of EPS aggregate, the concrete with higher volume of EPS aggregate shows higher moisture migrations. Since EPS aggregates are non-absorbent type, the possibility for different moisture migrations may be due to the shrinkage of EPS aggregate [16]. This can be confirmed from the higher moisture migrations of low density concretes (1000 kg/m^3). These concretes have higher volumes of EPS, therefore the spacing between the EPS aggregates is very small, i.e., the thickness of matrix between the aggregates is small. If the aggregates shrink, the matrix surrounded by the aggregates may suffer micro-cracking which cause higher moisture migrations. Whereas, in the case of higher density concretes, the amount of micro-cracking may be insignificant as the amount of EPS aggregate is less.

For the same EPS aggregate volume, the concrete made with bigger size EPS aggregate (Type Q) shows higher moisture migrations. The concrete with bigger EPS aggregates may shrink more and this may result in more micro-cracks compared to small sized EPS aggregate (Type

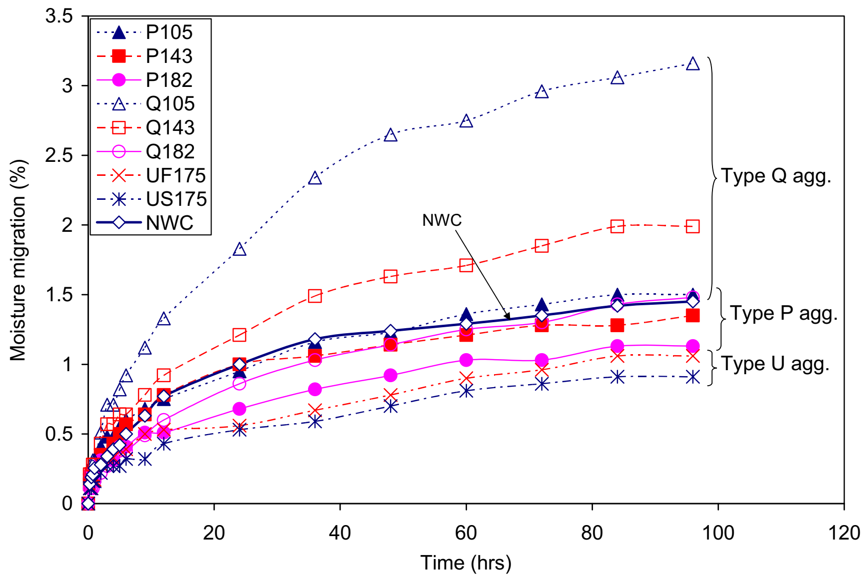

Fig. 5. Variation of moisture migration with time.

P). This can be clearly seen from the Fig. 5 where the concrete with Type Q (bigger size) aggregate shows two times higher moisture migration than concrete with Type P (smaller size). Moreover, the concrete containing UEPS aggregates also results in lower moisture migrations than NWC. This is because the un-expanded aggregate is strong and the shrinkage due to drying may be insignificant.

3.4. Water absorption

The variation of water absorption with time for the concretes containing EPS and UEPS aggregate is shown in Fig. 6. It shows that similar to moisture migration, the absorption results of EPS concrete increased with increase in the size and volume of the EPS aggregates. It also indicates that most of the concretes containing EPS and UEPS aggregates show lower absorptions than NWC. EPS concrete with lower density (1000 kg/m^3) showed higher absorption than NWC. However, higher density concrete (1800 kg/m^3) showed lower absorption than NWC. The concrete containing UEPS aggregate made with 35% fly ash (UF175) and 10% silica fume (US175) showed considerably lower absorption than NWC. The lower absorption in EPS and UEPS aggregate concrete may be due to the non-absorbent nature of aggregate and changes in the pore structure of the hydrated cementitious system caused by the use of supplementary cementing materials [23].

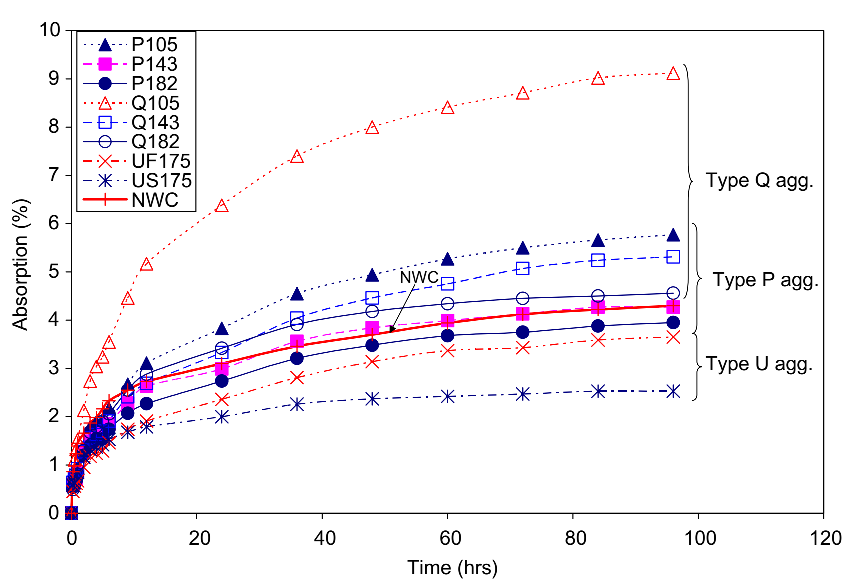

Fig. 6. Variation of water absorption with time.

A limit on the 30 min absorption for assessing the concrete quality has been defined by CEB [26]. The assessment criteria for EPS concrete containing 50% fly ash was discussed earlier [16]. The EPS concretes containing 30% fly ash showed absorptions ranging between 0.27% and 1.11% at 30 min, where higher value correspond to lower concrete density (Q105) and bigger size EPS aggregate (Type Q). As per the assessment criteria given by CEB, all 30% fly ash concretes were showing a low absorption rating (<3% absorption), indicating a "good" concrete quality, just as in the absorptions of EPS concrete containing silica fume [15]. The absorption in EPS concrete made with OPC for the fresh concrete densities ranging between 815 and 980 kg/m^3 reported were in the range of 21–27% of dry weight [4]. However, for comparable densities, EPS concrete made with fly ash showed 50% lower absorptions than EPS concrete made with OPC only [3]. The lowest absorptions in this study may be attributed to the pore filling caused due to the pozzolanic reactivity of fly ash [27].

In general, the lightweight concrete with wide range of densities (500–1900 kg/m^3) can be achieved by introducing different fillers (air, porous lightweight aggregate, etc.) [2,3]. The durability performance of higher density lightweight concretes produced by introducing air (aerated concrete) and artificial porous lightweight aggregate may be comparable to the concrete made with EPS aggregate. However, in the case of lightweight concrete with densities lower than 1200 kg/m^3, the water absorptions were more than 20% for aerated concrete [5] and more than 30% for porous lightweight aggregate concrete [28]. Therefore, these concretes may not be suitable for applications where durability or high resistance to water penetration is required. Whereas, the concrete made with EPS aggregate did not suffer that problem due to the non-absorbent nature of EPS aggregate. The 30 min absorption for these concrete also showed very low absorptions which are comparable with earlier studies [15,16]. The earlier reports on durability performance also suggested higher resistance of EPS concretes to water and chloride permeability, and resistance to chemicals [15,16,24]. From this, it can be concluded that lightweight EPS concretes are very cost effective and which can be used as damp proof course in buildings and road sub-bases.

4. Conclusions

For the same size of aggregate and comparable concrete density, concretes containing UEPS aggregate shows higher compressive strength (35 MPa) than EPS aggregate (20 MPa). The concretes containing EPS aggregate shows higher rate of strength gain than UEPS aggregate. Under compressive loading, concretes containing EPS aggregate show more gradual and ductile failure. However, the concrete containing UEPS aggregate exhibited brittle failure similar to NWC.

For comparable density, EPS concretes with smaller size EPS aggregate shows higher compressive strength. Concrete densities vary significantly with change of EPS volume. The proposed equation for the relation between compressive strength and density of different EPS concretes ranging from 200 to 2000 kg/m^3 is given by $f_c = 10.3 * \gamma^{1.918} * 10^{-6}$.

For similar mix proportions, the EPS concretes containing smaller size EPS aggregate and lower amounts of aggregate show higher splitting tensile strength. The proposed equation for the relation between splitting tensile strength and compressive strength of different EPS concrete is given by $f_{ct} = 0.2416 * f_c^{0.7933}$.

For similar mix proportions, the EPS concretes with bigger size EPS aggregate and concretes with higher volume of EPS aggregate (or concretes with lower densities) show higher moisture migration. Micro-cracking due to the shrinkage of EPS aggregate seem to be resulting in higher absorption.

EPS concrete containing fly ash showed low absorption rating as per the assessment criteria given by CEB with a "good" concrete quality. These show comparable or even lower moisture migration and absorption than NWC. UEPS concrete containing fly ash and silica fume exhibited lowest absorption.

Acknowledgements

The present work is part of the more comprehensive R&D program entitled "Development of high strength lightweight concretes with and without aggregates" jointly funded by Building and Construction Authority of Singapore (BCA) and National University of Singapore (NUS). The financial support from BCA and NUS is gratefully acknowledged.

References

[1] ACI Committee 213R-0.3. Guide for structural lightweight aggregate concrete. American Concrete Institute, Farmington Hills, MI, 2003.
[2] Sussman V. Lightweight plastic aggregate concrete. J Am Concr Inst Proc 1975;72:321–3.
[3] Bagon C, Frondistou-Yannas S. Marine floating concrete made with polystyrene expanded beads. Mag Concr Res 1976;28:225–9.
[4] Kearsley EP, Wainwright PJ. Porosity and permeability of foamed concrete. Cem Concr Res 2001;31:805–12.
[5] Short A, Kinniburgh W. Lightweight concrete. 3rd ed. London: Applied Science Publishers Ltd.; 1978.
[6] Cook DJ. Expanded polystyrene concrete. In: Swamy RN, editor. New concrete materials. Concrete technology and design, vol. 1. London: Surrey University press; 1983. p. 41–69.
[7] Godwin A. Versatile concrete blocks for the third world. Indian Concr J 1982:240–1.
[8] Hanna AN. Properties of expanded polystyrene concrete and applications for pavement sub-bases. Research and Development Bulletin, Portland Cement Association, 1978 (Rd 055.01P).
[9] Perry SH, Bischaff PH, Yamura K. Mix details and material behaviour of polystyrene aggregate concrete. Mag Concr Res 1991; 43:71–6.
[10] Bischoff PH, Yamura K, Perry SH. Polystyrene aggregate concrete subjected to hard impact. Proc Inst Civil Eng 1990;89(2):225–39.
[11] Sussman V, Baumann GH. Expanded polystyrene beads lighten the load. Soc Plastic Eng J 1972;28:18–21.

[12] Sivasundaram V, Carette GG, Malhotra VM. Long-term strength development of high-volume fly ash concrete. Cem Concr Compos 1990;12:263–70.
[13] Malhotra VM. Durability of concrete incorporating high-volume of low-calcium (ASTM Class F) fly ash. Cem Concr Compos 1990;12:271–7.
[14] Mehta PK. Pozzolanic and cementitious by-products in concrete-another look. In: Malhotra VM, editor. Proceedings of the 3rd international conference on the use of fly ash, silica fume, slag and natural pozzolans in concrete ACI, 1989, SP-114. p. 1–43.
[15] Ganesh Babu K, Saradhi Babu D. Behaviour of lightweight expanded polystyrene concrete containing silica fume. Cem Concr Res 2003;33:755–62.
[16] Ganesh Babu K, Saradhi Babu D. Performance of fly ash concretes containing lightweight EPS aggregates. Cem Concr Compos 2004;26:605–11.
[17] Saradhi Babu D, Ganesh Babu K, Wee TH. Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. Cem Concr Res 2005;35:1218–23.
[18] ACI Committee 211.2-91. Standard practice for selecting proportions for structural lightweight concrete. ACI Manual of Concrete Practice Part 1, 1997.
[19] Ganesh Babu K, Siva Nageswara Rao G. Efficiency of fly ash in concrete with age. Cem Concr Res 1996;26:465–74.
[20] Roy RL, Parant E, Boulay C. Taking into account the inclusions' size in lightweight concrete compressive strength prediction. Cem Concr Res 2005;35:770–5.
[21] Al-Manaseer AA, Dalal TR. Concrete containing plastic aggregates. Concr Int 1997:47–52.
[22] Laukaitis A, Zurauskas R, Keriene J. The effect of foam polystyrene granules on cement composite properties. Cem Concr Compos 2005;27:41–7.
[23] Ramezanianpour AA, Malhotra VM. Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash or silica fume. Cem Concr Compos 1995;17:125–33.
[24] Ravindrarajah RS, Tuck AJ. Properties of hardened concrete containing treated expanded polystyrene beads. Cem Concr Compos 1994;16:273–7.
[25] Li G, Stubblefield MA, Garrick G, Eggers J, Abadie C, Huang B. Development of waste tire modified concrete. Cem Concr Res 2004;34(12):2283–9.
[26] CEB-FIP. Diagnosis and assessment of concrete structures – State of the Art Report. CEB Bull 1989;192:83–5.
[27] Neville AM. Properties of concrete. 4th ed. Essex (England): Addison Wesley Longman; 1997.
[28] Kluge RW, Sparks MM, Tuma EC. Lightweight aggregate concrete. ACI J 1949:625–42.