

Lightweight Geopolymer Concrete with EPS Beads

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Abstract

Activation of class F fly ash with the 10 M sodium hydroxide and sodium silicate and its geopolymeric products were analysed under quasi-isothermal mode of DSC, FTIR and TG/DTA techniques. Before adding in concrete, expanded polystyrene beads were prewetted with the styrene-butadiene-styrene latex aimed at to improve their bonding with geopolymer. Lightweight mortars/concretes were made from geopolymeric binder, hardener and expanded polystyrene beads as part replacement of normal aggregates to various densities (800 -1840 kg/m³). The expanded polystyrene beads were added in the mix in the range of 1 -3% by wt. (40 - 91% by vol.). It was observed that increasing concentration of expanded polystyrene beads reduces compressive strength, split tensile strength and oven-dry density of the resulting mortars/concretes. Fire performance of expanded polystyrene/geopolymer concrete assessed by a cone calorimeter and reaction to fire characteristics methods was below the limits prescribed in the BS EN: 476 and ISO: 5660-1: 2002 and exhibiting no support to growth of the fire. However, it was noted that heat release rate and effective heat of combustion of expanded polystyrene concrete were higher than the control due to inclusion of expanded polystyrene bead aggregates in the mix. The thermal conductivity was reduced by 27-50% when expanded polystyrene beads were added in the geopolymer mixes to a level of 0.5-3% by wt. The properties of expanded polystyrene/geopolymer concrete were also compared with the existing guidelines (ASTM C 90).

Keywords: Geopolymer, Expanded polystyrene beads, Lightweight concrete, Fire behavior, Thermal conductivity

1. Introduction

Geopolymers have increasing interest world wide as an alternative to ordinary Portland cement for concrete due to limited reserve of limestones, limited manufacturing growth of cement and increasing carbon taxes. The additional motivation for exploring this alternative is attributed to its high early compressive strength, low drying shrinkage, good fire resistance and superior durability in aggressive environment compared to Portland cement concrete (Davidovits 2008; Provis and Deventer 2009). In general, geopolymers are produced through reactions between the alumino-silicate reactive materials (metakaoline, slag, fly ash etc) and chemical activators under high pH condition and their strength and microstructural properties were thoroughly studied under fresh and hardened states

(Palomo et al. 1999; Steveson and Sagoe-Crentsil 2005; Duxon et al. 2007; Latella et al. 2008). Knowing their potential as alternative binders, several attempts have been made on use of geopolymers to produce mortars, concrete, bricks, composites, high temperature resistant coatings etc. in building construction sector (Hardjito et al. 2004; Fernandez-Jiminez 2006; Yang et al. 2009; Kong and Sanjayan 2010; Zhang et al. 2010). A number of key aspects related to geopolymers such as mix proportioning, alkali-aggregate reaction, short and long term strength, bonding with metallic reinforcement and durability in various environments have been studied and very high strength has been achieved. However, the challenges remain to develop better understanding on controlling the setting processes of geopolymers related to end use conditions and also their repeatability in properties during industrial production using variable material sources.

In the present work, the main objective of project is to produce lightweight geopolymer concrete using expanded polystyrene (EPS) beads as part replacement of the normal aggregates for precast building components and also in sandwich construction. The selection of EPS bead aggregate was made mainly due to its low density, closed cellular structure, hydrophobic and energy absorbing characteristics. Previously, several studies were conducted on mix details, strength properties, drying shrinkage, compaction & finishing etc. of the polystyrene aggregate concretes (Perry et al. 1991; Ravindrarajah and Tuck 1994; Ismail et al. 2003; Babu and Babu 2004). They reported that the properties of EPS concretes are affected by the water-cement ratio, volume percentage of EPS beads, mineral admixture, adhesion between EPS bead and cementitious binder and segregation of EPS beads in the mix. It is also discussed that the hydrophobic nature of EPS beads in concrete requires either the use of bonding additives (Cook 1983) or their chemical treatments (Perry et al. 1991). While EPS aggregate concrete is widely researched, geopolymer based lightweight concrete has become the subject of intense research interest. Also, the information on performance of EPS/geopolymer lightweight concrete are not available in the literature with particular reference to its behavior on insulation and fire performance. At CSIR-Central Building Research Institute, a systematic study has been initiated on development of geopolymer based construction material using fly ash as a basic raw material. As a result, several geopolymer products such as light weight concrete, bricks, blocks, foam etc. have been developed.

In this paper, we report properties of lightweight geopolymer concrete with different percentage of EPS bead aggregate. Reaction products formed during geopolymerization were studied by DSC, FTIR and TG/DTA techniques. Performance of EPS/geopolymer concretes was discussed in relation to their flammability and insulation characteristics. The properties of these concretes were also compared with the existing standard specifications.

2. Experimental

2.1. Materials

Class F fly ash collected from coal fired thermal power corporation (Surathgarh, India) has been used in this investigation (SiO_2 57.55%, Al_2O_3 31.40%, Fe_2O_3 7.50%, CaO 1.40%, moisture content 1.5%, loss of ignition 2%). The ash contains spherical solid particles and

cenospheres with a wider particle size distribution (D10: 0.40 μm ; D50 : 1.23 μm ; D90 : 5.39 μm). The Blains surface area of fly ash was 350 m^2 / kg with 80% particles passing through 45 μm sieve on a dry sieving and 88% on a wet sieving. Two types of beads : 4.75 - 8 mm (specific gravity, 0.014) and 1- 4.75 mm (specific gravity, 0.029) were used. Natural sand of fineness modulus 2.3 and 10 mm down sand stone coarse aggregates of fineness modulus 6.9 (impact value 16.3 %; crushing strength value 15.43% and los angles abrasion value 25.42%) were used. Polycarboxylate based superplasticizer (Glenium 51) and styrene butadiene styrene latex (SBR, BASF Make) were used as received. Reagent grade sodium hydroxide (97.5% purity) and sodium silicate (Na_2O 8%, SiO_2 28%, and water 65%) were procured from the local market.

2.2. Preparation of samples

Various concentrations of activating solutions were prepared by mixing NaOH and sodium silicate in 1:2.5 ratio. The solution was then cooled for 24 hrs prior to its use. Subsequently, fly ash was thoroughly mixed with the activating solution in a laboratory mixer for 5-10 min to obtain a homogeneous paste. The cured pastes were used for FTIR and thermal analysis.

The mix proportion of EPS/ geopolymer mortar / concrete is given in Table 1. The EPS beads were first prewetted with SBR latex and kept for 2 hrs to improve its wettability. The dry mix consisted of fly ash, treated EPS beads and fine/coarse aggregate were prepared in a concrete mixture. Subsequently, geopolymer solution (10M) mixed with superplasticizer (2 % by wt.) was added into dry mix and blended for 6-8 minutes to obtain homogenous mixture. The resulting mix was poured into moulds, hand compacted and vibrated for 2-3 minutes at low speed. It is cautioned that over vibrations should be avoided to prevent upward movement of EPS beads in mixture. A lower slump maintained the cohesiveness and body of the mix. The specimens were covered with plastic sheets for 24 hrs after casting and then, cured at 60 $^{\circ}\text{C}$ for 4-6 hrs. The cubes (100 mm^3), cylinders (100 x 200 mm) and plates (300 x 300 x 30 mm) were cast. The EPS beads were added in the range of 0.5 - 3% of total mix by wt. (40-91% by vol.).

2.3. Methods

The heat flow during the geopolymerization reaction was measured by a differential scanning calorimetry (DSC - TA Instruments Inc.) under quasi - isothermal mode with 0.4 amplitude and 5 $^{\circ}\text{C} / \text{min}$ heating rate. The sample was prepared by mixing fly ash (3.5 g) and 10 M alkaline activator (1.75ml). The thermogram of prepared samples was recorded at different temperatures (27 $^{\circ}\text{C}$, 80 $^{\circ}\text{C}$ and 100 $^{\circ}\text{C}$). TG /DTA thermal analyser (Perkin Elmer - Pyris Diamond) was used to record weight loss and phase change in the samples. The test run was conducted in the temperature range of 27 - 1000 $^{\circ}\text{C}$ under nitrogen atmosphere at 10 $^{\circ}\text{C} / \text{min}$ heating rate.

FTIR spectrophotometer (Perkin Elmer- GX) was employed to record IR spectra of hardened pastes in the transmittance mode. The hardened pastes containing different activator concentrations were ground into a fine powder, mixed with KBr (1% by wt.) and

Table 1: Mix proportions of EPS/geopolymer mortar/concrete

(Coarse aggregate content: 200, 400, 600 kg/m³ ; Molarity: 10 M; Liquid binder ratio: 0.3 - 4.5; Superplasticizer : 2% by wt.)

Fly ash (kg/m ³)	Alkaline solution (kg/m ³)	Sand (kg/m ³)	Coarse aggregates (kg/m ³)	EPS beads (%)	
				by wt	by vol
922.5	300	180	-	-	-
922.5	300	180	-	1 -3	40-91
1000	345	75	-	-	-
1000	345	75	-	1-3	40-91
1000	300	180	1000	2	75

pressed in the form of pellet. The spectra were recorded from 4000 - 600 cm⁻¹ with a resolution of 4cm⁻¹.

The compressive strength of samples (100 mm cube) was tested as per ASTM C 39-2012 at a loading rate of 0.25 mm/min. The split tensile strength of samples was tested as per ASTM C 496-2011 at a loading rate of 0.25 mm/min. The thermal conductivity of composite samples (300 x 300 x12 mm) was measured using a guarded hot plate conductivity apparatus according to BIS: 3346-1990. The average of the three samples was reported.

Cone calorimeter (FTT Ltd.) has been used to measure flammability characteristics of the EPS/geopolymer concrete according to ISO 5660-1: 2002. The test run was conducted for 20 min at the heat flux of 50 Kw/m² and normal duct flow rate of 24 l/s. The ignitability, fire propagation index and surface spread of flame of samples were also tested as per BS EN 476 -1981(part 5, 6 &7).

3. Results and discussion

3.1. Geopolymer reactions

Figure 1 shows quasi-isothermal DSC traces of geopolymer reactions at different temperatures. As the reaction proceeds, two exothermic peaks were noticed after 4 min and 10 min corresponding to dissolution of fly ash and condensation reactions between dissolved silicon and aluminium species (Buchwald et al. 2009). As observed in the curves, the dissolution of fly ash was more at 100 °C than the dissolution at 27 and 80 °C whereas the condensation reaction peak at 80 °C was higher than those of others. This indicates that geopolymerization reaction at 80 °C may exhibit more stable aluminosilicate network structures. Extending the reaction times, the curves were featureless showing the

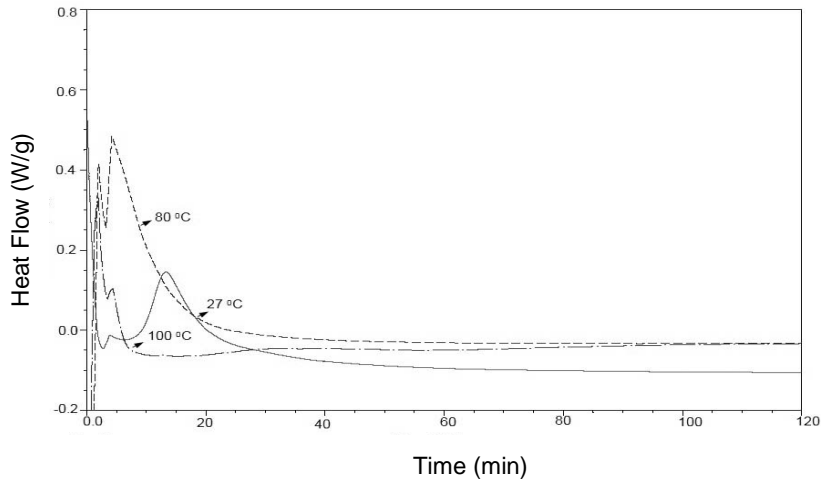


Figure 1 : DSC run under quasi-isothermal mode of samples at different temperatures

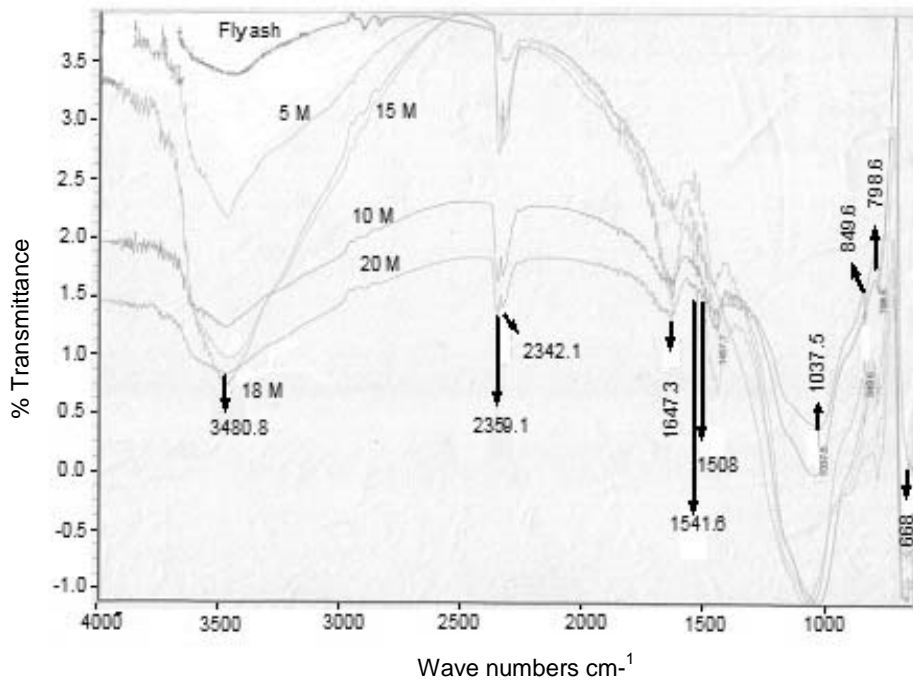


Figure 2: FTIR spectra of geopolimer pastes containing different molar concentrations of activator

occurrence of structural re-organization processes probably due to the particle growth and inter-particle bonding. FTIR spectra of hardened pastes at different activator concentrations are shown in Figure 2. The formation of aluminosilicate network can be viewed in terms of its intense peak assigned at 3480 cm^{-1} (-OH group), new absorption band at 1647 cm^{-1} (H_2O) and Si-O band at $\sim 1100\text{ cm}^{-1}$ (stretching) and at 849 cm^{-1} (bending) compared to fly ash starting material. The shifting of Si-O peak around 1100 cm^{-1} towards lower wave numbers indicative of re-organization of network due to long Si-O bond and also enriched Si-O-Al bonds (Simonsen et al. 2009). It was noted that the peak shift was sensitive to the activator concentration. The existence of intense -OH and H_2O peaks are attributed to the water released during condensation step of geopolimerization. This water existed as an independent state in the geopolimer gels and thus, becoming a source of porosity in the hardened structures because of its non-participation in the curing process. The thermal

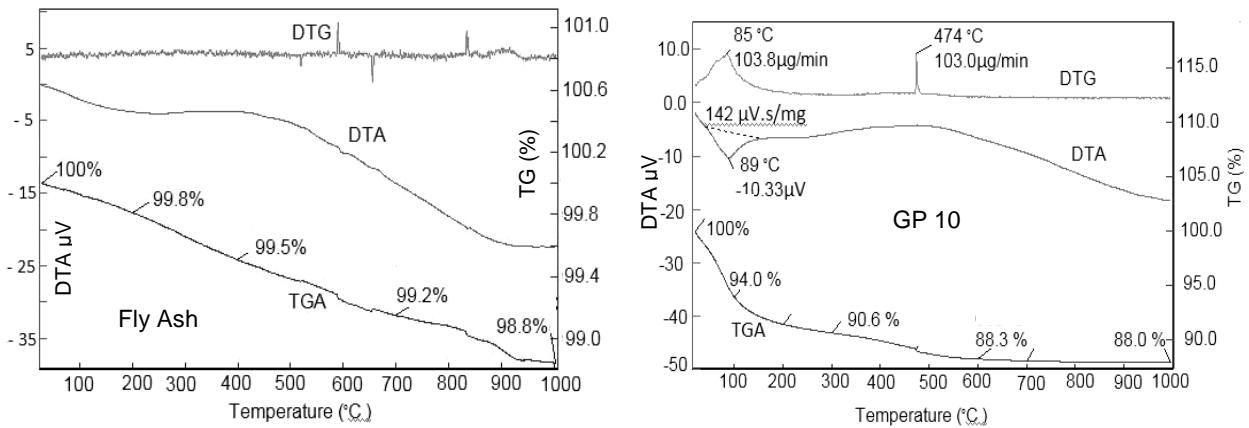


Figure 3: TGA/DTA curves of fly ash and geopolymer pastes

stability of these network systems was assessed by TGA/ DTA (Fig. 3). The weight loss in the samples occurred ~ 7% upto 200 °C probably due to moisture and adsorbed / bounded water compared to 0.2% weight loss for fly ash starting material. In DTG curve, peaks in various samples between 77 and 84 °C may be considered due to the evaporation of water. It was reported that bounded water in the aluminosilicate gel affected strongly to the properties of hardened structure such as compressive strength, thermal shrinkage etc. Between 600 - 1000 °C, the weight loss in the samples appeared to be constant probably due to the formation of nepheline and albite type phases in the microstructure (Provis and Deventer 2009). A broad exothermic region (250 - 600 °C) in the DTA curve indicated the restructuring of sodium - aluminosilicate and other phases.

3.2 Properties of EPS/geopolymer mortar/ concrete

Figure 4 shows compressive strength of geopolymer mortars as a function of EPS aggregate content. As the percentage of EPS beads increased, the compressive strength of mix decreased. The strength reduction occurred in the range of 38% to 60% at a level of 1% by wt. (~40% by vol) for both sizes of EPS beads in the mix. It was noted that a decrease in the strength was more when large size of EPS beads (4.75 - 8 mm) were added in the mortars due to their less surface area / volume ratio. The split tensile strength of samples also decreased with the increase of EPS beads aggregate. The EPS beads added in the mix contributes only to its low density. The oven-dry densities of mortars were reduced by ~22 % and ~ 46% at 40% and 91% by vol. EPS beads addition respectively. At oven-dry density of 800 kg/m³ for insulation, the compressive strength of samples remained 0.8 MPa only. The lowering of strength may be considered due to the inherent weak strength of EPS beads in compression and also the presence of pores and voids in the mix. The fractured surfaces revealed that EPS beads were distributed uniformly in the mix and adequately bonded with geopolymer because the prewetted EPS with SBR latex and viscous mix with slump of 15-20 mm were used in the casting of samples. The adaptation of fast setting of geopolymer with the help of hardening agent may also be reasoned to overcome floating and segregation of EPS in the mortar.

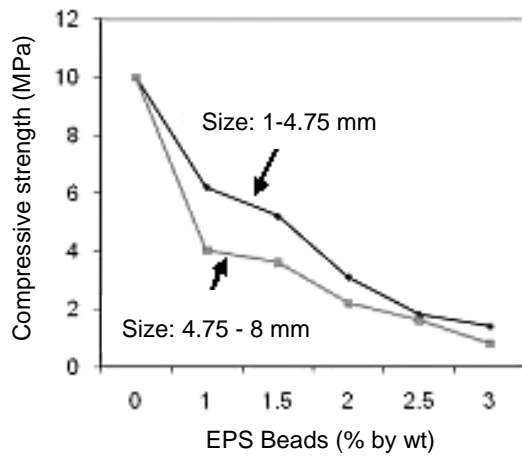


Figure 4: Compressive Strength of mortar vs EPS bead content

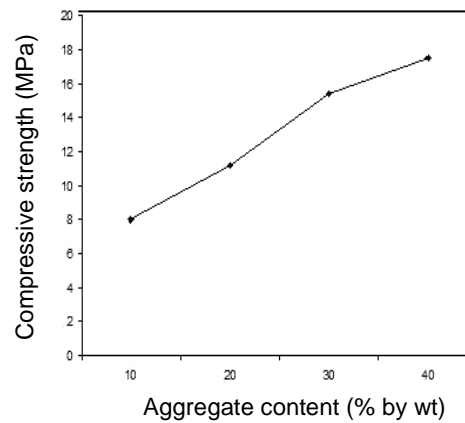


Figure 5: Compressive Strength of EPS/geopolymer concrete vs aggregate content

Light weight concretes were prepared using geopolymer, prewetted EPS beads (~ 2% by wt., 1 - 4.75 mm), natural sand, coarse aggregates (10 mm down) and superplasticizer (2% by wt.). The oven-dry density of these concretes ranged between 1500 and 1840 kg/m³ and their water absorption varied from 3 to 5%. Adding coarse aggregate increased the compressive strength (Fig. 5) and oven-dry density of EPS/geopolymer mix. It was observed that compressive strength (7.5MPa) of EPS/geopolymer concrete can possibly meet the minimum specified criteria of ACI guidelines (ACI 213R - 03) for lightweight concrete (compressive strength 17 MPa and oven-dry density 1120 -1920 kg/m³). To meet the requirements of insulation concrete, the addition of < 20% coarse aggregates (10 mm down) into EPS/geopolymer mix exceeds compressive strength (~15 MPa) as specified (13.1 MPa) in ASTM C 90.

3.3 Fire behavior

Flammability data of EPS/geopolymer concrete obtained from cone calorimeter are given in Table 2. It was observed that geopolymer concrete had negligible heat release rate, total heat release and effective heat of combustion. The total oxygen required to flash out the samples was 0.6 g only. This indicates that geopolymer does not contribute to the rate of fire spread. By the addition of EPS in geopolymer concrete, the heat release rate, total heat release and the effective heat of combustion increased to 9.63 kW/m², 6.8 MJ/m² and 3.75 MJ/kg respectively. The samples consumed about 13.8 g oxygen for their ignition compared to 0.6 g oxygen for the control. Because of this, mass loss (12.6 g) and mass loss rate (0.023g/s) were higher than the control samples (mass loss, 1.8 g and mass loss rate, 0.01g/s). The samples exhibited ~ 18.1% more carbon dioxide yield. It was noted that the total smoke release in the EPS/geopolymer concrete was ~ 13% less than the samples without EPS beads probably due to release of more water vapors in the smoke from the control samples. Because of this, the control samples had higher specific extinction area than the EPS samples indicating more visible smoke. The time of ignition for EPS/geopolymer concrete was 19 seconds at 50 kW/m² heat flux compared to 425 seconds of the control. This can be explained on the basis of EPS beads ignition existed on the surface under higher temperature.

Table 2: Cone calorimeter results of EPS/ geopolymer concrete

Property	Geopolymer concrete	EPS / geopolymer concrete
Total heat release (MJ/m ²)	0	6.8
Heat release rate (kW/m ²)	0	9.63
Average mass loss rate (g/s)	0.01	0.023
Average effective heat of combustion (MJ/kg)	Nil	3.75
Carbon monoxide (kg/kg)	0.073	0.037
Carbon dioxide (kg/kg)	1.05	1.24

The fire performance of samples was also tested for their ignitability, surface spread of flame and fire propagation index. During ignitability test, the sample did not flame after application of test flame for 10 seconds. Based on results, the sample was categorized under 'P' - not easily ignitable type. When pilot flame was applied to the sample to know its surface spread flame behavior, there is no charring on its surface even at the contact point of igniting flame. However, the surface became slightly reddish. The exposed surface of samples was free of cracks. The spread of flame on the surface of sample was not noticed after 10 minutes exposure to the radiant panel. Based on the observations, the sample was classified in Class I- surface of very low spread of flame. To assess the contribution towards fire growth, the fire propagation index of samples was calculated from time-temperature data as per BS: 476 (part 6). It was found that fire propagation index of samples was < 3 exhibiting no support to the fire growth. It was concluded that EPS/geopolymer concrete exhibited satisfactory fire performance as observed from cone calorimetric parameters and reaction to fire tests.

3.4 Thermal insulation

The thermal conductivity of EPS/geopolymer mortar in various densities (1000 - 1840 kg/m³) was measured by a guarded hot-plate. The curve shows a dependency of thermal conductivity on the density of samples (Fig. 6). The difference in the values may be considered due to matrix density and microstructure. Increasing concentration of EPS beads decreases thermal conductivity of the samples. The thermal conductivity was reduced by 27-50% when EPS beads are added in the geopolymer mortars to a level of 3% by weight. The thermal conductivity value of EPS/geopolymer concrete was in the range of 0.427-0.852 W/mK. It is concluded that geopolymer concrete can be engineered by proper selection of variables for making lightweight materials comparable to cement concrete.

3.5 Durability studies

The performance of geopolymeric paste was studied under acidic and sulphate environment for a period of 4 months. It is observed that loss of compressive strength was 26% in the

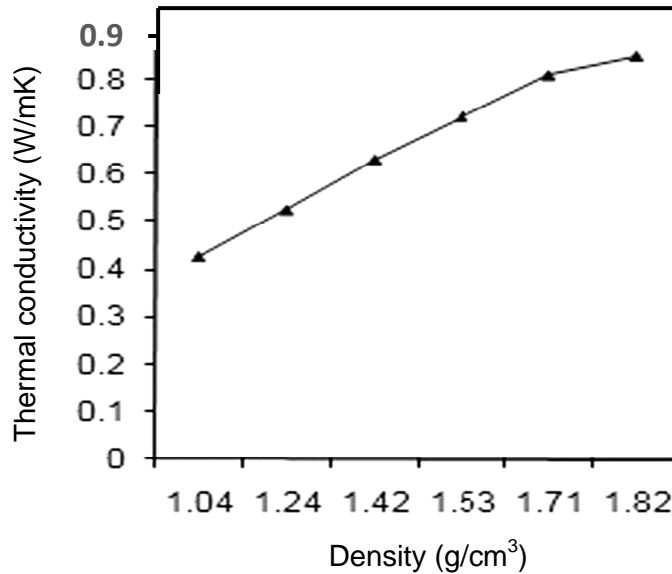


Figure 6: Thermal conductivity of geopolymer mortar vs density

sodium sulphate solution and 50% in the magnesium sulphate solution. The samples were cracked in the mixed solution of the sodium sulphate and magnesium sulphate after 30 days. On the other hand, the samples exposed under acidic environment exhibited 39% strength reduction in the HCl and 54% in the H₂SO₄ solutions. It is noted that the loss of geopolymer strength in the deionized water was ~ 25%. The weight gain in the acidic environment was 1.4% while the samples gained 3% weight in sulphate solution. The performance of these materials can be improved by optimally formulated activators in making cross-linked network structure (Singh et al. 2011).

4. Conclusions

Results indicate that expanded polystyrene beads can be effectively used as part replacement of the normal aggregates in making lightweight geopolymer concrete in different densities. The mix was cohesive with SBR latex prewetted EPS beads. The floating and segregation of EPS beads can be minimized by using low slump of mix and fast setting of geopolymer with hardener. The compressive strength and split tensile strength decreased with the increase of EPS bead aggregate. Flammability results indicate that EPS geopolymer concrete exhibited no support to the growth of fire. The thermal conductivity reduced significantly when EPS beads were added to geopolymer mortar/concrete. The developed concrete can satisfy the minimum requirement of ACI guidelines (ACI 213 R) and ASTM C 90. It is concluded that EPS/geopolymer concrete can be successfully used in precast building components and also for insulation purpose.

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References

- ACI Committee 213 R, Guide for Structural Lightweight Aggregate Concrete, 2003.
- Babu K G and Babu S B (2004) “ Performance of Fly Ash Concretes Containing Lightweight EPS Aggregates.” *Cement and Concrete Composites* **26**: 605-611
- Buchwald A, Tatarin R and Stephan D (2009) “Reaction Progress of Alkaline - Activated Metakaoline - Ground Granulated Blast Furnace Slang Blends.” *Journal of Material Science* **44**: 5609-5617.
- Cook D J (1983) “ Expanded Polystyrene Concrete”, in Swamy R N (Ed), *Concrete Technology and Design, New Concrete Materials*, vol. 1, 41-69, Survey University Press.
- Davidovits J (2008) “*Geopolymers: Chemistry and Applications*”, Institute Geopolymer, Paris.
- Duxon P, Jimenez AF, Provis JL, Luckey G C, Palomo A and Veventer J V (2007) “ Geopolymer Technology: The Current State of the Art, *Journal of Material Science* **42**: 2917-2933.
- Fernandez-Jiminez A M, Palomo A and Lopez- Hombrados C (2006) “ Engineering Properties of Alkali- Activated Fly Ash Concrete .” *ACI Materials Journal* **103**: 106-112.
- Hardjito D, Wallah S E, Sumajouw M J and Rangan B V (2004) “ On the Development of Fly Ash Based Geopolymer Concrete.” *ACI Materials Journal* **101**: 467-472.
- Ismail I, Saim A A and Saleh A L (2003) “Properties of Hardened Concrete Bricks Containing Expanded polystyrene Beads.” *Proceedings of the 5th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2003) 26 - 28 August 2003, 171-179, Johor Bahru, Malaysia.*
- Kong D L V and Sanjayan J G (2010) “ Effect of Elevated Temperatures on Geopolymer Paste, Mortar and Concrete.” *Cement and Concrete Research* **40**: 334-339.
- Latella, B.A., Perera, D.S., Durce, D., Mehrtens, E.G. and Davis J. (2008) “Mechanical Properties of Metakaolin-based geopolymers with Molar Ratios of Si/Al~ 2 and Na/A ~ 1”, *Journal of Material Science*, 43: 2693-2699.
- Palomo A, Grutzeck M W and Blanco M T (1999) “ Alkali- Activated Fly Ashes: A Cement for the Future.” *Cement and Concrete Composites* **29**: 1323-1329.
- Perry S H, Bischoff P H and Yamura K (1991) “ Mix Details and Material Behavior of Polystyrene Aggregate Concrete.” *Magazine of Concrete Research* **43**: 71-76.

Provis J L and Deventer S J V (2009) “ *Geopolymers-Structure, Processing, Properties and Industrial Applications.*” CRC Press, Woodhead Publishing Ltd., Great Abington, Cambrid, UK.

Ravindrarajah R S and Tuck A J (1994) “Properties of Hardened Concrete Containing Treated Expanded Polystyrene Beads.” *Cement and Concrete Composites* **16**: 273 – 277.

Simonsen M E, Sonderby C, Li Z and Sogaard E G (2009) “XPS and FTIR Investigation of Silicate Polymers.” *Journal of Material Science* **44**: 2079 - 2088.

Singh B, Sharma S, Gupta M and Bhattacharyya SK (2011) “ Performance of Fly ash based Geopolymer Pastes under Chemical Environment.” *Paper presented at International Conference on Advances in Construction Materials through Science and Engineering, 5-7 September, 2011, Hong Kong.*

Stevenson, M. and Sagoe-Crentsil, K. (2005) “Relationships between Composition, Structure and Strength of Inorganic Polymers”, *Journal of Material Science*,**40**: 4247-4259.

Yang K H, Song J K, Lee K S and Ashour A F (2009) “ Flow and Compressive Strength of Alkali-Activated Mortars.” *ACI Materials Journal* **106**: 50-58.

Zhang Z, Yao X and Zhu Z (2010) “ Potential Application of Geopolymers as Protection Coatings for Marine Concrete I: Basic Properties.” *Applied Clay Science* **49**: 1-6.