BEARING STRENGTH OF CONCRETE CONTAINING POLYSTYRENE AGGREGATE

Bearing strength of concrete

R.SRI RAVINDRARAJAH
Centre for Built Infrastructure Research, Faculty of Engineering,
University of Technology, Sydney, Australia.

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Abstract

Concrete has the ability to withstand a higher concentrated load over part of its area than the load placed over its entire area. Previous studies on the bearing capacity of normal weight concrete indicated that the bearing strength is related to the compressive strength and the total area to bearing area ratio. This paper reports the results of an experimental investigation into the bearing strength of polystyrene aggregate concrete as a function of the bearing area and compressive strength.

Expanded polystyrene granulates can be used with the conventional concrete making materials to produce lightweight polystyrene aggregate concrete, having a wide range of performance characteristics. Normal weight high-strength concrete mixture, having the compressive strength of about 80 MPa, was modified to produce reductions in density of concrete by replacing varying amounts of the coarse aggregate with expanded polystyrene beads. Using 200 mm concrete cube specimens, the bearing strength of polystyrene aggregate concrete was determined. Square and circular bearing area shapes were used and the bearing area was varied from one-half to one-eighth of the total area. The bearing strength (f_b) for polystyrene aggregate concrete is given by the following empirical expression: $f_b = (0.635 + p)\, f_c' \,(R)^{0.5}$ where p is a coarse aggregate replacement level by polystyrene, R is the ratio of total area to bearing area and f_c' is the concrete compressive strength obtained from a cylinder test. The failure pattern under the bearing load was found to vary with the decrease in the density of polystyrene aggregate concrete. The lightweight polystyrene particles are found to enhance the durability of concrete when it is either subjected sulphate attack or freeze-thaw cycles.

Keywords: Bearing strength, compressive strength, durability, expanded polystyrene, failure pattern, lightweight concrete

1 Introduction

Lightweight expanded polystyrene in the form of spherical beads or irregular granulates can be used with conventional concrete making materials to produce lightweight concrete mixtures with a wide range of densities. The polystyrene particles have a negligible water absorption capacity due to its closed cellular structure. Cook (1973) reported that the use of untreated polystyrene particles had created difficulties in achieving a uniform dispersion in the concrete matrix due to the hydrophobic nature as well as to the lightness of the polystyrene. Sri Ravindrarajah and Tuck (1994) reported that when the polystyrene beads are coated with an inert chemical, having the hydrophilic property, segregation is eliminated and the polystyrene aggregate content can be easily increased to produce lightweight concrete.

Bischoff et. al. (1989) reported that the polystyrene aggregate concrete has an excellent energy absorbing property, hence it is suitable for applications to reduce the effect of impact loading. Sri Ravindrarajah and Naji (1993) reported that the polystyrene aggregate concrete is capable of accommodating sulphate contaminated materials without significant damage. Lai et. al. (1996) studied the behaviour of reinforced concrete beams with polystyrene aggregate concrete and the results showed increase in short-term deflection with no change in the cracking behaviour when compared with similar beams having the normal weight concrete with equal strength.

Concrete has the ability to withstand a higher concentrated load over part of its area than of a load placed over its entire area. The bearing capacity of normal weight concrete has been widely studied by Meyerhof (1953), Shelson (1957), Tung and Baird (1960), Hawkins (1968), Haagsma (1969), Niyogi (1973), Williams (1979) and Lieberum (1989). A cone or failure wedge is formed under the loaded area and this moves downward and causing splitting of the loaded specimens. The purpose of this study is to investigate the effects of the inclusion of polystyrene beads on the bearing capacity and failure process of concrete.

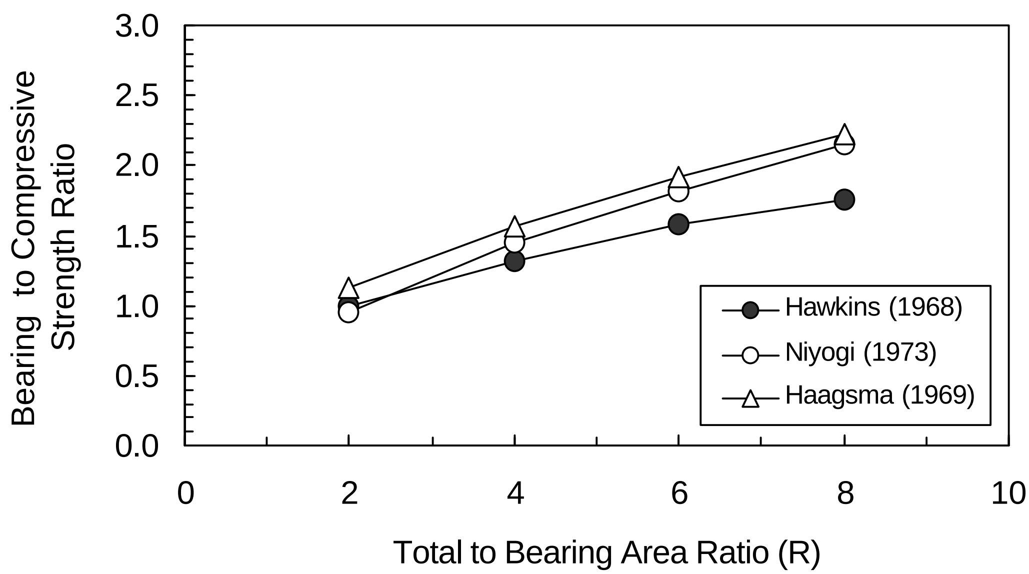

Fig. 1: Bearing strength of normal weight concrete as a function of compressive strength and bearing area

2 Background

It is known that the concrete is able to higher bearing stresses than its compressive strength. Tung and Baird (1960) based on Coulomb/Mohr theory of rupture suggested the failure under bearing stresses as a sliding process along planes inclined to the direction of the principal stresses. The resistance to sliding is brought about by the strength of internal cohesion of the material and by the resistance of each constituent to internal friction. Lieberum and Reinhardt (1989) reported that allowable stresses under concentrated loading conditions could be higher than the predicted design stress due to the improvement in concrete strength when the transverse strain is confined. Figure 1 shows the relationship between ratio of bearing strength to cylinder strength and cylinder strength proposed by Hawkins (1968), Niyogi (1973) and Haagsma (1969).

The proposed equation for bearing strength of concrete by Haagsma (1969) is similar to that adopted by ACI Building Code (1989). The bearing strength (f_b) = 0.79 f_c (A_c/A_b), where f_c is the compressive cube strength, A_c is the total area of concrete and A_b is the area of concrete under the bearing load. An increase in the ratio of the total area to the bearing area produces a significant increase in the bearing strength due to the confinement provided by the non-loaded area of concrete. Tests conducted by Meyerhof (1953) displayed sliding failure in concrete due to the formation of a distinctly separate cone under a circular base plate. Shelson (1957) observed the formation of an inverted pyramid in concrete under small base plates and under larger base plates an internal pyramid was formed.

3 Experimental Details

3.1 Materials and mixture compositions

General purpose Portland cement (Type GP), similar to ASTM Type I, conforming to AS 1319 was used as the binder material in all concrete mixtures. Crushed basalt (specific gravity of 2.65), having a maximum aggregate size of 10 mm, and coarse river sand (specific gravity of 2.62) were used as coarse and fine aggregates, respectively. A superplasticiser (high-range water-reducing admixture) consists of a salt of naphthalene sulphonate formaldehyde condensate was used. Spherical shaped expanded polystyrene beads (specific gravity of 0.67) with a mean diameter of 3 mm was used. They were coated with an inert chemical to improve the adhesion and dispersion of them within the concrete matrix.

The control concrete mixture is a normal weight high-strength concrete. It had the following mixture compositions: 460 kg/m^3 of cement; 161 kg/m^3 of water; 735 kg/m^3 of river sand; and 1105 kg/m^3 of basalt. The water to cement ratio of this mixture is 0.35 and 270 ml/m^3 of the superplasticiser was used to achieve sufficient workability. By replacing 10, 20 and 30% of the coarse aggregate by *solid* volume with the polystyrene beads, three polystyrene aggregate concrete mixtures were produced. The quantities of the superplasticiser used were 280, 300 and 340 ml/m^3 for the concrete mixtures with 10, 20 and 30% of coarse aggregate replacements with the polystyrene aggregate, respectively.

3.2 Batching, mixing and preparation of test specimens

Experience had shown that a proper mixing sequence is necessary to produce a uniform polystyrene aggregate concrete mixture. Coarse aggregate, fine aggregate and cement were first placed in a pan-type mixer and dry mixed for about five minutes. Then, the required amount of the polystyrene beads was added and the dry mixing was continued for another two minutes. Finally, the water was gradually added to the mixture while the mixing process was in progress. The superplasticiser was introduced by thoroughly mixing it with the mixing water.

For each concrete mixture, a number of 100 mm diameter by 200 mm high standard cylinders were moulded in steel moulds for compressive strength testing at the age of 28 days. In addition, a number of 200 mm cubes were moulded in specially-made timber moulds for the bearing strength test. A table vibrator was used to compact the fresh concrete in the moulds.

3.3 Curing and testing of specimens

The test specimens were stripped from their moulds after 24 hours and stored in a water bath at 23 $\pm$ 2 ^{o}C until the age of testing at 28 days. The cylinders were tested in direct compression while the cubes were subjected to bearing load through either circular or square 15 mm thick steel plates. The bearing area was varied to produce the ratios of total area to bearing area of 2, 4, 6 and 8. The bearing plates used are 70.7, 81.7, 100 and 141.4 mm square and 79.8, 92.2, 112,8, and 159.6 mm diameter circular in shape. The bearing plates were positioned centrally on one of the formed surfaces of the 200 mm cubes and the compressive load was gradually applied on the cubes at a rate of 60 MPa per minute through the bearing surface. For each concrete mix, two identical specimens were tested for the same total area to bearing area ratio (R) and the same shaped base plate.

4 Results and discussion

4.1 Workability and unit weight of polystyrene aggregate concrete

Although no workability test was conducted on fresh concrete mixtures, visual examination and handling experience indicated that the polystyrene aggregate concrete mixtures became stiff and rubbery with the increase in the polystyrene aggregate content. In addition to the use of vibrating table, it was found necessary to use a modified tamping rod with a circular disc attached to achieve a proper compaction. While finishing the moulded specimens, some difficulties were encountered to obtain smooth surface. The polystyrene aggregate particles caused small lumps on the surface of the concrete and this proved difficult to trowel.

The control concrete mixture had the unit weight of 2455 kg/m^3. When the coarse aggregate particles were replaced with polystyrene beads by equal *solid* volumes corresponding to 10, 20 and 30%, the unit weight (wet density) of the concrete mixture was reduced to 2330, 2210 and 2080 kg/m^3, respectively.

It was noted that the measured values for the unit weight were lower than those expected due to entrapped air voids in compacted concrete. The entrapped air content for the control mix was 0.41% and for the polystyrene aggregate concrete mixtures were 1.06, 1.56 and 2.80%, respectively for the mixtures having the aggregate replacement levels of 10, 20 and 30%, respectively.

4.2 Compressive strength of polystyrene aggregate concrete

Unit weight is the most important physical property of concrete in relation to the strength of concrete. Figure 2 shows the effect of unit weight on the cylinder strength of concrete. As expected, a decrease in the unit weight of concrete produced a significant reduction in the cylinder strength of concrete. When the unit weight decreased from 2455 to 2330 kg/m^3 (a decrease of 5%), the cylinder strength dropped from 79 to 56 MPa, (a drop of 29%). When the unit weight decreased by 10 and 15%, the cylinder strength decreased by 51 and 65%, respectively. This showed that the relationship between the void content and compressive strength is non-linear. The 28-day cylinder strength for the polystyrene aggregate concrete with the lowest unit weight of 2080 kg/m^3 is 28 MPa, hence this concrete can be considered as a lightweight structural concrete.

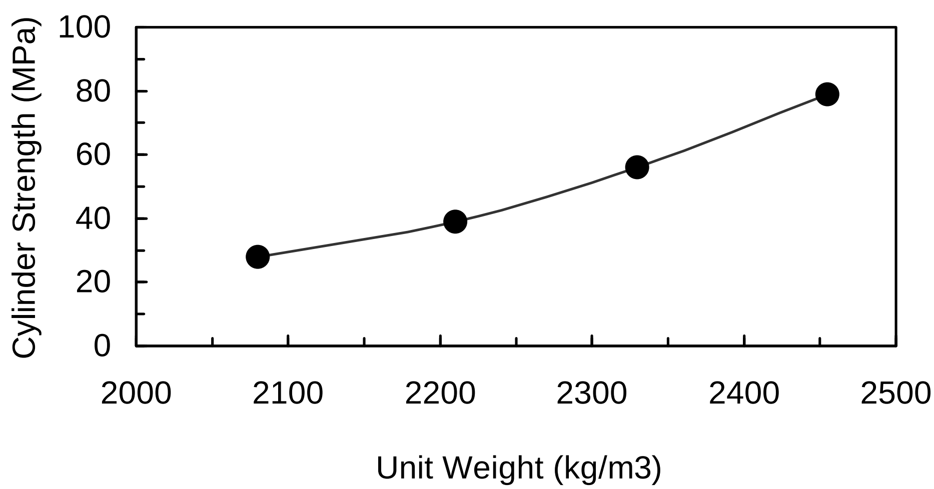

Fig. 2: Relationship between unit weight and compressive strength

Table 1: Bearing strength (MPa) of polystyrene aggregate concrete

Polystyrene Content (%)	**Unit Weight (kg/m^3)**	**Cylinder Strength (MPa)**	**Bearing Area Shape**	**Bearing Strength (MPa)**			
				R* = 2	**R = 4**	**R = 6**	**R = 8**
0	2455	79	Square	80	96	120	136
			Circle	80	105	119	138
10	2330	56	Square	62	74	101	114
			Circle	59	80	96	111
20	2210	39	Square	51	66	82	96
			Circle	52	65	82	95
30	2080	28	Square	39	53	66	75
			Circle	40	52	67	74

*Note: R = Total Area / Bearing Area

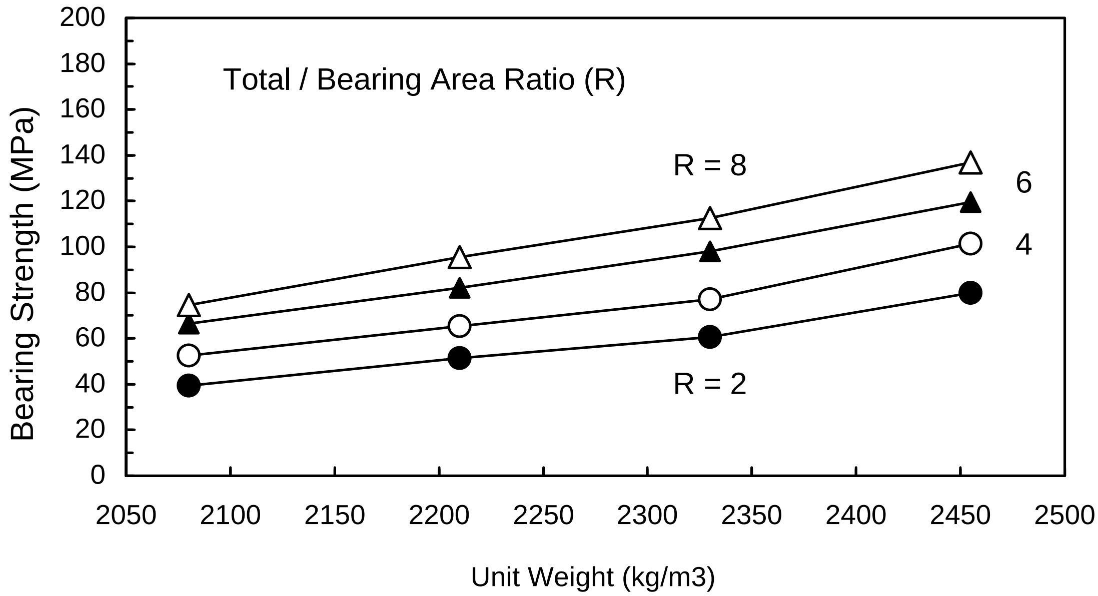

Fig. 3: Effect of unit weight, bearing area on bearing strength of polystyrene aggregate concrete

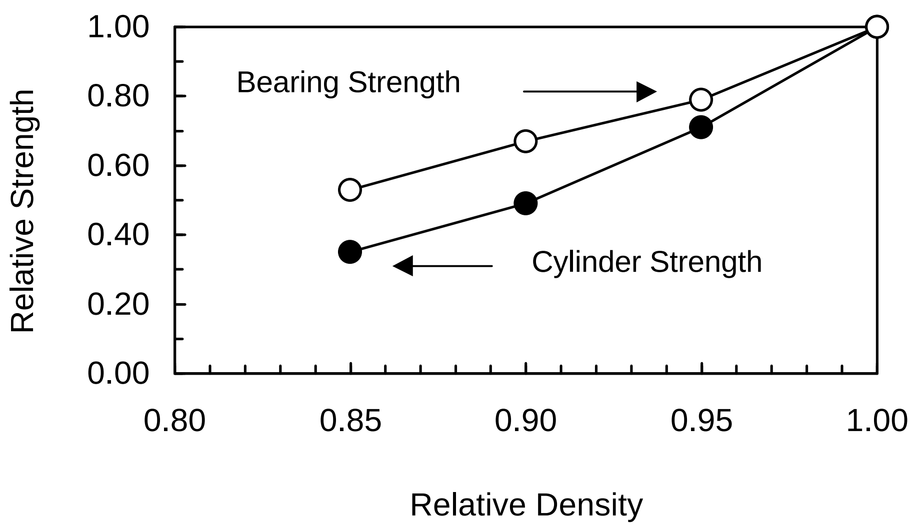

Fig. 4: Relationship between relative strengths in compression and bearing and relative density for polystyrene aggregate concrete

4.3 Bearing strength of polystyrene aggregate concrete

Table 1 summarises the results obtained from bearing strength tests for the control concrete and three polystyrene aggregate concrete mixtures when square and circular shaped bearing plates were used. The total to the bearing area ratio was varied from 2 to 8. For a given total to bearing area ratio (R), the bearing strength values obtained with the square and circular base plates do not differ significantly. Figure 3 is plotted using the mean values obtained with both square and circular base plates. Hence, each point in this plot is the mean of four results obtained with four identical test specimens. The results shown in Fig. 3 indicate that the bearing strength increased with the increase in the total to the bearing area ratio, independent of the unit weight of concrete.

Figure 4 shows the bearing and cylinder strengths of polystyrene aggregate concrete in relation to those for the control concrete. For the bearing strength, each point shown in this plot is the mean of 16 readings taken with both square and circular base plates having different sizes, whereas the compressive strength is the mean of 3 readings from three identical cylinders.. Similar to the compressive strength, a decrease in the unit weight produced significant reductions in the bearing strength of concrete. However, the compressive strength is more sensitive to the unit weight than the bearing strength. When the unit weight is decreased by 15%, the compressive strength and the bearing strength decreased by 65% and 47%, respectively.

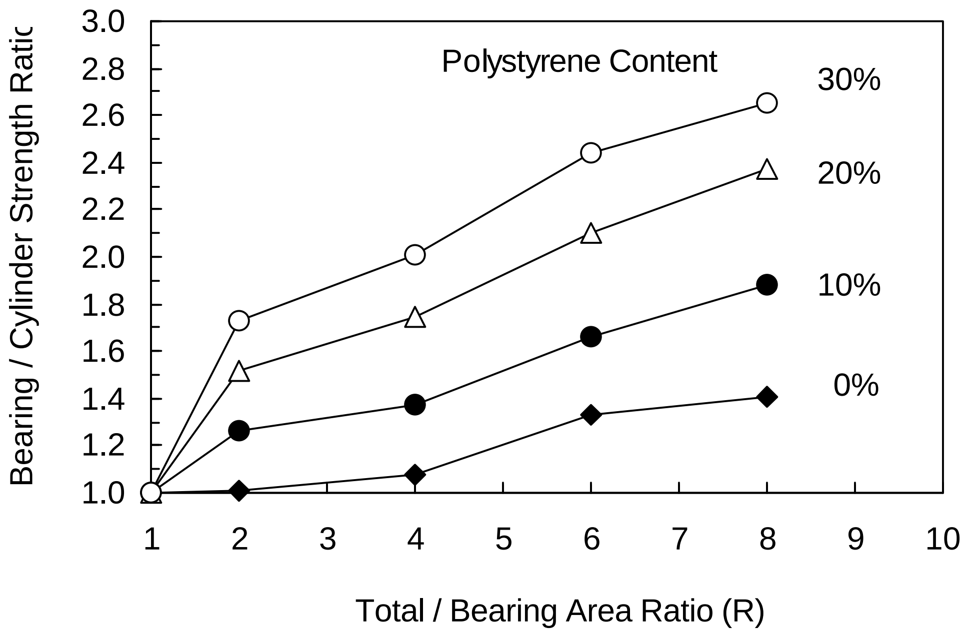

Fig. 5: Relationship between bearing to cylinder strength ratio and total to bearing area ratio (R)

4.4 Relationship between bearing strength and cylinder strength

Figure 5 shows the relationship between the ratio of bearing strength to cylinder strength and the ratio of total area to bearing area for the control concrete and polystyrene aggregate concretes. For a given ratio of total area to bearing area, the polystyrene aggregate concrete showed significantly higher values for the ratio of the bearing strength to the cylinder strength than those for the control concrete. With the increase in the ratio of total area to bearing area, the polystyrene aggregate concrete showed significant bearing strength in relation to its compressive strength. For the polystyrene aggregate concrete with the unit weight of 2080 kg/m^3 and the bearing area of one-eighth of the total area, the bearing strength is 2.66 times of cylinder strength.

However, for the control concrete for the same bearing condition the corresponding value is only 1.48.

As mentioned earlier, ACI Building Code (1989) considered that the ratio of the bearing strength to the compressive strength is proportional to the square root of the the ratio of the total area to the bearing area. Using the results obtained in this investigation, the following empirical equation was developed for the bearing strength (f_b) of polystyrene aggregate concrete in relation to the cylinder strength (f_c'), polystyrene aggregate content and the total area to bearing area ratio.

$$f_b = (0.635 + p)\,(A_c/A_b)^{0.5}\,f_c' \qquad \textbf{(1)}$$

The factor 0.635 represents the governing design value that incorporates the mixture parameters and testing arrangements. Haagsma (1969) proposed a factor of 0.79 when cube strength is used. Since the cylinder strength is 80 per cent of cube strength, then the factor changes to 0.632, when cylinder strength is considered. The second factor 'p' is equal to the polystyrene aggregate content in relation to coarse aggregate replacement. As an example, when 20% of coarse aggregate is replaced with the polystyrene aggregate, the value for 'p' is 0.20. It was found that as the ratio of the total area to the bearing area is increased, the predicted bearing strength using Eqn. (1) is within $\pm$ 5 MPa of the measured values.

4.5 Bearing strength design consideration

AS3600 (1994) states that the design bearing stress at the concrete surface should not exceed [ϕ 0.85 f_c $(A_c/A_b)^{0.5}$] or 2 ϕ f_c (which ever is less) where A_c is the bearing area and A_b is the largest area of the supporting surface that is geometrically similar to and concentric with A_c. ϕ is the strength reduction factor of 0.6, which is lower than 0.7 used by ACI Code (1989). Comparing the results obtained in this study, it can be shown that both ACI Code (1989) and AS3600 (1994) are applicable to the polystyrene aggregate concrete as well.

4.6 Failure process under bearing loading

Under the application of the bearing load, it was noticed that shortly before the failure occurred vertical cracks initiated at the top of the test cubes and propagated downward in each of the four sides or corners indicating splitting due to sliding failure. The maximum load was reached shortly after the cracks appeared and started to propagate. Typical cone failure of the specimens was noted for both square and circular base plates. The failure wedge under the base plate was of conical shape for the circular plate whereas a pyramidal shape was observed for the square plate.

When the bearing area is half that of total area, cone type failure was not observed. The failure appeared to be a sliding failure in a vertical direction. This may have occurred due to the limited amount of transverse confinement available.

The failure for the control concrete under bearing load was sudden, indicating the brittle nature of high-strength concrete. With the inclusion of polystyrene aggregate the failure was more gradual, indicating the energy absorbing capability of the expanded polystyrene aggregate particles. For the polystyrene aggregate concrete, the base plates were found to move into the specimens considerably under the increasing bearing load. Once the maximum load was reached, the load carrying capacity was gradually decreased due to the ductile behaviour of the polystyrene aggregate concrete. After the failure, the cracked sections remained intact.

The circular and square plates produced different initial crack initiation and propagation patterns on the specimens under the bearing load. Under the circular plates cracks tend to propagate to the nearest edge of the specimens from the base plate, whereas with the square plates the cracks propagated towards the extreme corners or near corners of the specimens. These cracks are formed the results of the stress concentrations developed at the corners of the square plates.

4.7 Durability of polystyrene aggregate concrete

The studies reported by Sri Ravindrarajah and Naji (1993) indicated that polystyrene aggregate concrete is capable of allowing higher proportions of sulphate ions without causing significant expansion than that allowed for the control normal weight concrete. Sabaa (1998) reported that the polystyrene aggregate concrete with the density between 1750 and 1850 kg/m^3 showed no reduction in its dynamic modulus of elasticity when it was subjected to 450 cycles of freezing and thawing. Hence, these studies indicate that polystyrene aggregate concrete is more durable under severe exposure conditions than the normal weight concrete. The polystyrene aggregate particles act as energy absorbing component in the concrete system, thus negating the disruptive expansive stresses created by the changes in the exposure conditions or by the chemical attack.

5 Conclusions

a) The bearing strength of polystyrene aggregate concrete is increased with an increase in the ratio of total area to bearing area. With the increase in the polystyrene aggregate content, the ratio of the bearing strength to the compressive strength increased

b) An increase in the polystyrene aggregate content reduced the bearing strength of concrete but to a reduced extent when compared with the compressive strength.

c) The bearing strength of polystyrene aggregate concrete can be predicted by using the equation: $f_b = (0.635 + p) (A_c/A_b)^{0.5} f_c'$, where f_c' is the cylinder strength, 'p' is the polystyrene content based on coarse aggregate replacement, A_c and A_b are the total area and bearing area, respectively.

d) ACI 318 (1989) and AS3600 (1994) are conservative in their approach to design requirements for bearing strength of concrete and they are equally applicable to the polystyrene aggregate concrete.

e) The base plate shapes used, square and circular, had no significant influence on the bearing strength for the polystyrene aggregate concrete, although different failure patterns were observed.

f) Inclusion of expanded polystyrene aggregate particles induces ductility to the concrete and the failure process was changed from brittle to ductile due to the energy absorption capability of the polystyrene particles.

g) Polystyrene aggregate concrete is more durable when it is subjected to sulphate attack or freeze-thaw cycles.

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