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Polystyrene Aggregate Concrete

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PREFACE

This study was designed to improve the building and construction industry's understanding of polystyrene aggregate concrete. The three specific tests undertaken were tests for strength, shrinkage and thermal insulation performance.

ACKNOWLEDGMENTS

This work was funded by the Building Research Levy.

READERSHIP

This report is intended for researchers and industry members interested in lightweight aggregate concrete.

POLYSTYRENE AGGREGATE CONCRETE

BRANZ Study Report SR 85 **S.G. Park and D. H. Chisholm**

REFERENCE

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KEYWORDS

Aggregates; Concrete; Lightweight Concrete; Polystyrenes

ABSTRACT

A study of concrete made with polystyrene beads as aggregate was carried out. Three different densities were investigated, and at each density, mixes both with and without fly ash were examined. It was found that polystyrene concrete is very prone to segregation, has low compressive strength and has a relatively high drying shrinkage for the densities investigated. Thermal conductivity testing showed that the lighter the concrete, the lower the thermal conductivity. Adding fly ash to the mixes decreased the water demand, and hence the density and shrinkage, but also caused a significant compressive strength reduction.

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1. INTRODUCTION

There are many advantages to be gained from the use of lightweight concrete. These include lighter loads during construction, reduced self-weight in structures, and increased thermal resistance. Lightweight concrete is generally accepted as concrete having a density of about 1800 kg/m^3 or less.

Lightweight concrete is normally made in one of three ways (New Zealand Portland Cement Association, 1980); by using lightweight aggregates, aeration or gas, or by making a no fines concrete. In all three cases the reduction in the concrete density is achieved through an increase in the air voids in the concrete.

Expanded polystyrene beads are often used as the basis for packaging material. This leads to a large amount of waste material which is not biodegradable. This material could be granulated and used as a lightweight aggregate for concrete.

Study of overseas commercial literature, e.g. Building Systems Technology (BST®) (1992), shows that polystyrene is being used as aggregate in lightweight concrete systems. This lightweight concrete is available as precast panels which can be easily handled, cut with power tools or even hand saws, and erected quickly and simply. Alternatively, expanded polystyrene (EPS) beads, coated in a substance which reduces the hydrophobic behaviour of EPS, can be used when mixing the concrete. The beads are virgin EPS, not recycled.

A literature survey found very little in the way of research results with regard to polystyrene concrete made from either virgin or recycled EPS. Some work has been carried out by Sri Ravindrarajah and Tuck (1993) from the University of Technology, Sydney. They investigated the compressive strength, tensile strength, static modulus of elasticity, ultrasonic pulse velocity, drying shrinkage and chemical resistance of BST® polystyrene concrete with densities of 1300 kg/m^3 and 1400 kg/m^3. They also investigated the inclusion of silica fume in the mixes.

Work was also carried out by the Cement and Concrete Association of New Zealand (C&CA) in 1991 (C&CA, 1994). This limited study, which examined the strengths and some drying shrinkages of recycled EPS concrete with densities ranging from 700 to 1700 kg/m^3, showed that waste granulated polystyrene can be used to manufacture lightweight concrete with similar strength to polystyrene bead concrete. The study highlighted difficulties in compaction and finishing of concretes with densities below 1000 kg/m^3.

Two of the suggestions for further study, included in the summary of that C&CA report, were thermal insulation capacity and drying shrinkage. Much is made, especially in commercial literature, e.g. BST® (1992), of polystyrene aggregate concrete's thermal resistance properties. This current research was designed to address these issues. The idea also was to expand on the work already done by the C&CA by using different mix designs to help develop an improved understanding of the characteristics of polystyrene concrete, particularly for densities below 1000 kg/m^3. To this end, samples were made to test for strength to NZS 3112: Part 2 (Standards Association of New Zealand, 1986), for shrinkage to AS 1012.13 (Standards Australia, 1992) and, to expand the earlier project, for thermal insulation performance to ASTM-C236-89 (American Society for Testing and Materials, 1989).

2. EXPERIMENTAL METHOD

2.1 Materials

It was decided to investigate mixes with target densities of 600 kg/m^3, 800 kg/m^3, and 1000 kg/m^3. Investigations were also made of mixes using fly-ash, at these same densities, to see if this would enhance the workability, and/or other properties of the mixes.

The mix designs used in the project are given in Table 1.

Table 1. Target mix designs.

Material	P600	PF600	P800	PF800	P1000	PF1000
Cement (kg/m^3)	350	230	400	270	450	300
Fly Ash (kg/m^3)	-	120	-	130	-	150
Sand (kg/m^3)	-	-	180	180	340	340
Polystyrene (loose packed l/m^3)	1000	1000	900	900	850	850
Water (l/m^3)	180	180	180	180	180	180

The original project carried out by the C&CA (C&CA, 1994) was an investigation into using recycled polystyrene as aggregate. There were some recycled polystyrene beads still left over from this project. A problem arose in getting more recycled polystyrene. The supplier of the original recycled polystyrene was no longer in business, and another supplier was not able to be found. The P600 mix was made from recycled polystyrene used in the C&CA program. The rest of the mixes were made from 'virgin' expanded polystyrene beads. Trial mixes carried out to compare the two different types of beads found that they both had the same water demand and workability characteristics.

2.2 Mixing

Before full-scale sample mixing was carried out, some small scale trial mixes were done to determine if the mix designs that were decided on would produce practical mixes. The mixes chosen were small (about 10 litres), and were mixed in a paddle mixer. The P600 and P800 mix designs, neither containing fly ash, were investigated. These demonstrated that the mix designs were viable. They also demonstrated that extreme care should be taken when adding the mix water as there was a very fine line between not having enough water and the paste being too stiff to mix well with the polystyrene beads, and adding too much water such that the paste was too thin, ran off and down through the beads and provided a fluid upon which the beads simply floated. Photographs of the results of these trials are given as Figures 1 and 2. Note the layer of paste that formed at the bottom of the 600 kg/m^3 mix is due to too much water being added.

The full-scale mixes were mixed in an 80-litre pan mixer. The mix order was to place all of the cement, sand and fly ash in the bowl, start the mixer, and add water until a slightly fluid paste was obtained. The polystyrene beads were then added. More water was then added until the mix could take no more without segregating. This water addition had to be judged by eye. The cement (type GP), fly ash, sand (Puketapu, F.M. approximately 2.75) and water were weigh batched. The polystyrene was volume batched.

For the purpose of thermal testing, panels were cast which were 1150 mm x 1150 mm x 100 mm. This required three mixes from the pan mixer for each mix type. For each different mix design the first mix would be made and the amount of water added was measured. Then, for the next two mixes, an identical quantity of water was added to each. This ensured uniformity over the three mixes.

The compression cylinders and shrinkage beams were made from the same polystyrene concrete as the slabs. Two cylinders and one shrinkage beam were made from each of the three mixes used for the slabs, allowing three 7-day and three 28-day compression cylinders and three shrinkage beams.

2.3 Workability

The workability characteristics of the polystyrene concretes were very different from normal concrete. Compaction by rodding or vibration was not effective owing to the lightweight nature of the mixes and the compressibility of the polystyrene beads. When rodded, the mix was simply displaced from where the tamping rod was inserted, and failed to fill in the hole left by the rod when it was withdrawn. Thus, from this point of view, the mix could be described as ‘stiff’.

The mixes were also very sticky or cohesive in that the cement slurry coating the polystyrene beads was very effective in holding the mix together. Owing to the light weight nature of the mix, it was very easy to displace the mix and move it around, and the mix stuck to anything that it came into contact with – the hand, the mould or mix to mix. From this point of view the mix, whilst stiff, was very workable. The slump test was not carried out as the mixes would not have been properly compacted in the slump cone, and when the cone was lifted, most of the mix would have lifted up with the cone. However, because of the lightweight, cohesive nature of the mixes, they had the ability to stand under their own weight without slumping.

Thus, cylinders and shrinkage beams could not be compacted according to their respective standards. The most effective way to compact the mixes was by the application of pressure. Cylinders were made in three layers. Each layer was compacted by gentle but firm hand pressure which aimed to press the beads together without actually compressing the beads themselves. The shrinkage beams were compacted in the same manner but in two layers.

A point to note here is that, in order to cure the shrinkage beams in lime saturated water for the initial seven days, they had to be weighed down or else they simply floated.

The panels for thermal testing were cast in a plywood form and were also compacted by the application of pressure. This was done both with hand pressure to get the polystyrene concrete into the corners, and with a wooden screed bar, which was also used to level and finish the top surface of the slabs.

3. RESULTS

3.1 Water Demand

The water demand for all of the mixes was significantly less than the 180 litre ‘design’ figure. Actual water demands are given in Table 2 below. The mixes containing fly ash required less water than those without. This is due to the plasticising effect of the fly ash. As expected, the water demand increased with increasing sand proportion.

Table 2. Actual water demand of all mixes.

Mix Designation	Water Demand (l/m^3)
P600	116
PF600	98
P800	123
PF800	111
P1000	152
PF1000	143

3.2 Workability and Finish

As described above, the mixes were very stiff and cohesive because of their low self weight, but were still workable. The mixes were very easy to place and move around. As long as the water content was carefully managed then there was no problem at all with segregation.

The surface finish that could be achieved with the concrete was dependent on the amount of paste in the mix.

The 600 kg/m^3 mixes only had enough paste to coat the beads and hold them together. This gave a very porous type of concrete. They were basically no-fines mixes.

The 800 kg/m^3 mixes, with their sand and increased cement contents, had enough paste to fill up most of the voids but still did not have enough to give a smooth surface finish.

The 1000 kg/m^3 mixes had enough paste to both fill all of the voids and give a reasonable surface finish.

The fly ash mixes did show an improvement in workability as witnessed by the reduction in the water demand for these mixes.

3.3 Strength and Densities

The strength and density results are given in Table 3 below. The densities were calculated on a weight per unit volume of the compression cylinders rather than using saturated surface dry weight in air and weight in water. This was due to the fact that a weight in water could not be obtained for the cylinders, as they floated. Strictly speaking, the densities given below are not saturated surface dry (SSD) densities as not all of the voids in the concrete were filled with water. Due to the very porous nature of the concrete, water simply ran out of the voids when the concrete was taken from a bath, say, into the air. We have called the density measured therefore the wet density as it was obtained when the cylinders were wet, but not saturated.

Table 3. Strength and density results.

Concrete	Age			
	7 Days		28 Days	
	Strength (MPa)	Wet Density (kg/m^3)	Strength (MPa)	Wet Density (kg/m^3)
P600	0.5	530	0.8	550
PF600	0.6	480	0.7	520
P800	3.2	820	3.8	820
PF800	1.4	760	2.1	760
P1000	5.5	1020	6.7	1040
PF1000	3.0	980	4.9	990

3.4 Drying Shrinkage

Table 4 below gives the 56-day results of the drying shrinkage testing. Graphs of the shrinkage are given as Figures 3 and 4.

Table 4. Polystyrene concrete 56-day shrinkage results.

Concrete	56-Day Shrinkage (Microstrain)
P600	2690
PF600	2290
P800	1840
PF800	1630
P1000	1300
PF1000	1260

3.5 Thermal Testing Results

The results of the thermal testing are given in Table 5 below. Both the R-value and thermal conductivity are given for each sample.

These results are displayed graphically in Figure 5. This shows close to a linear relationship between the densities of the different concretes and their thermal conductivities. The densities shown here are the air dry densities.

Table 5. Polystyrene aggregate concrete R-values and thermal conductivities.

Concrete	R-Value (m^2°C/W ±3%)*	Conductivity (W/m°C ±3%)
P600	0.746	0.134
PF600	0.755	0.132
P800	0.456	0.219
PF800	0.462	0.216
P1000	0.325	0.308
PF1000	0.342	0.292

* Based on 100 mm thick panel.

4. DISCUSSION

The water demands for all of the mixes was lower than anticipated. An excess of water resulted in the cement paste segregating from the polystyrene beads.

The polystyrene concrete mixes investigated in this project all displayed a very low workability. They behaved in a very 'sticky' or cohesive manner until too much water was added to the mix, and then very sudden segregation occurred. This caused problems when it came to compacting the concrete. Compacting cylinders in the standard manner, for example, was not possible due to the nature of the mix. The concrete had to be placed in layers and pressed. During the course of this project this pressing was carried out through the application of hand pressure. This may cause difficulties for site placement in practice. Methods would need to be developed to compact the concrete as normal vibratory techniques will probably not be effective.

Only the 1000 kg/m^3 mixes had enough paste to fill the voids and allow a well finished surface to be achieved. The 800 kg/m^3 and 600 kg/m^3 mixes had correspondingly less paste and hence, could not be finished as well. The 600 kg/m^3 mixes were like a no-fines mix, with just enough paste to coat the beads and hold them together.

The strength obtained by the mixes is very low given their cement content. This was expected due to the weakness, in compression, of the polystyrene aggregate. These results mean that it would not be possible to use these mix designs for structural concrete. It should also be noted that, even though using fly ash did allow for a reduction in the water demand, this was not sufficient to compensate for the 30% reduction in cement content in terms of strength.

As seen in Table 3 above, the P600 mix had a wet density of 550 kg/m^3 and the PF600 mix a wet density of 520 kg/m^3 at 28 days. This is lower than the 600 kg/m^3 that was targeted. The rest of the mixes achieved results which straddled their target densities with the fly ash mix coming in below, and the non-fly ash mix coming in above. The low density result for the 600 density mixes probably came about through the difficulty in compacting the concrete in the moulds. With the denser mixes the compaction process was easier, therefore, densities closer to those required were achieved.

The 56-day drying shrinkages measured for the mixes in this program were very high compared with normal density concrete. The results ranged from 1260 microstrain for the PF1000 mix to 2690 microstrain for the P600 mix. Testing carried out by the authors in the course of both commercial and research work shows that a normal density concrete would have a drying shrinkage somewhere in the range of 600 to 1000 microstrain. In each case the mixes incorporating fly ash had a lower drying shrinkage than those which were straight GP cement mixes. It is thought that this is due to the lower water demand of the fly ash mixes. With a lower water content, there is a lower shrinkage as the concrete dries out. The high drying shrinkage results were expected as polystyrene aggregate does not have the strength to restrain the high shrinkage of cement paste. In the higher density mixes the sand component will have had some restraining effect, hence these mixes had lower shrinkages.

The thermal conductivity results are what would be expected from material of the given densities, as can be seen in Figure 5. The curved line in this graph is from Arnold (1969) and is a best fit line through a large amount of data collected from many different experiments. It shows that this material behaves in the same manner, thermally, as other lightweight concrete materials. The less dense the concrete the lower the thermal conductivity.

5. CONCLUSIONS

1. Polystyrene aggregate concrete is very prone to segregation. Care must be taken to ensure that not too much water is added to the mix so as to prevent segregation from occurring.

2. Placing and compacting the polystyrene aggregate concrete can be quite difficult as normal vibratory compaction techniques do not work as well as with normal weight concrete. In this study the concrete was compacted by hand pressure.

3. Polystyrene aggregate concrete with densities less than 1000 kg/m^3 has very low strength for the quantity of cement that it contains. The mean 28-day compressive strength results ranged from 0.7 MPa for the P600 mix to 6.7 MPa for the P1000 mix. This is well below the strength required to be considered a structural concrete. The low strengths were expected due to the nature of the mix.

4. The mean 56-day drying shrinkages ranged from 1260 microstrain for the PF1000 mix up to 2690 microstrain for the P600 mix. These high values were expected given that cement paste has high shrinkage, and that polystyrene does not have the strength to resist this shrinkage. The lower shrinkages for the higher density mixes was due to the sand component of these mixes having a restraining effect.

5. The thermal performance of the different mixes was close to what would be expected for concretes of their densities. The lighter the concrete the lower the thermal conductivity.

6. Fly ash added to the mixes based on a 30% replacement rate on cement reduced the water demand and hence density and shrinkage, but also caused a significant compressive strength reduction.

7. The test results suggest that polystyrene concrete has scope for non-structural applications utilising low weight and low thermal conductivity eg. residential wall panels.

6. SCOPE FOR FURTHER WORK

Areas that were not investigated in this program, or the earlier C&CA program, in which it is felt that further work should be carried out include:

- Water absorption and/or permeability
- Reinforcement protection and bond
- Acoustic information e.g. sound transmission class
- Compaction techniques for full scale applications
- Fire performance.

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8. FIGURES

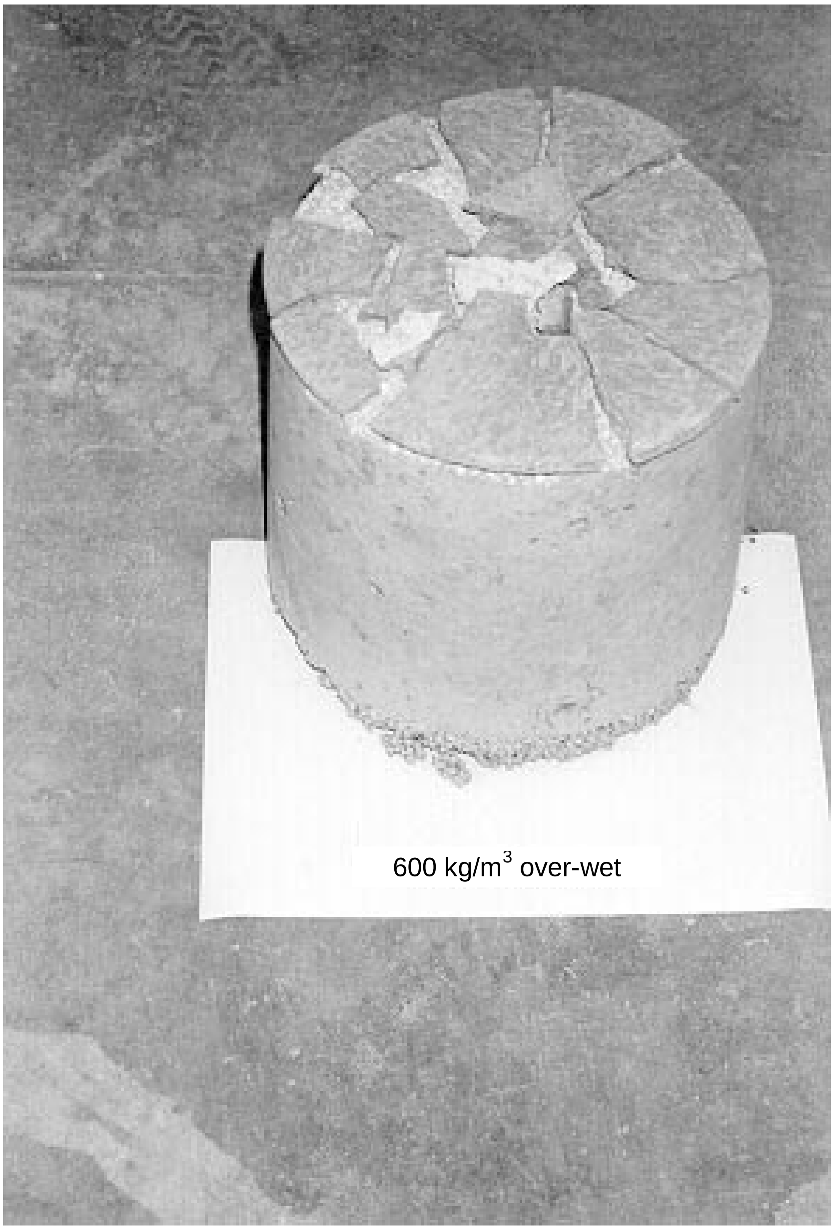

Figure 1. Bottom of the hardened P600 trial mix showing the result of too much mix water.

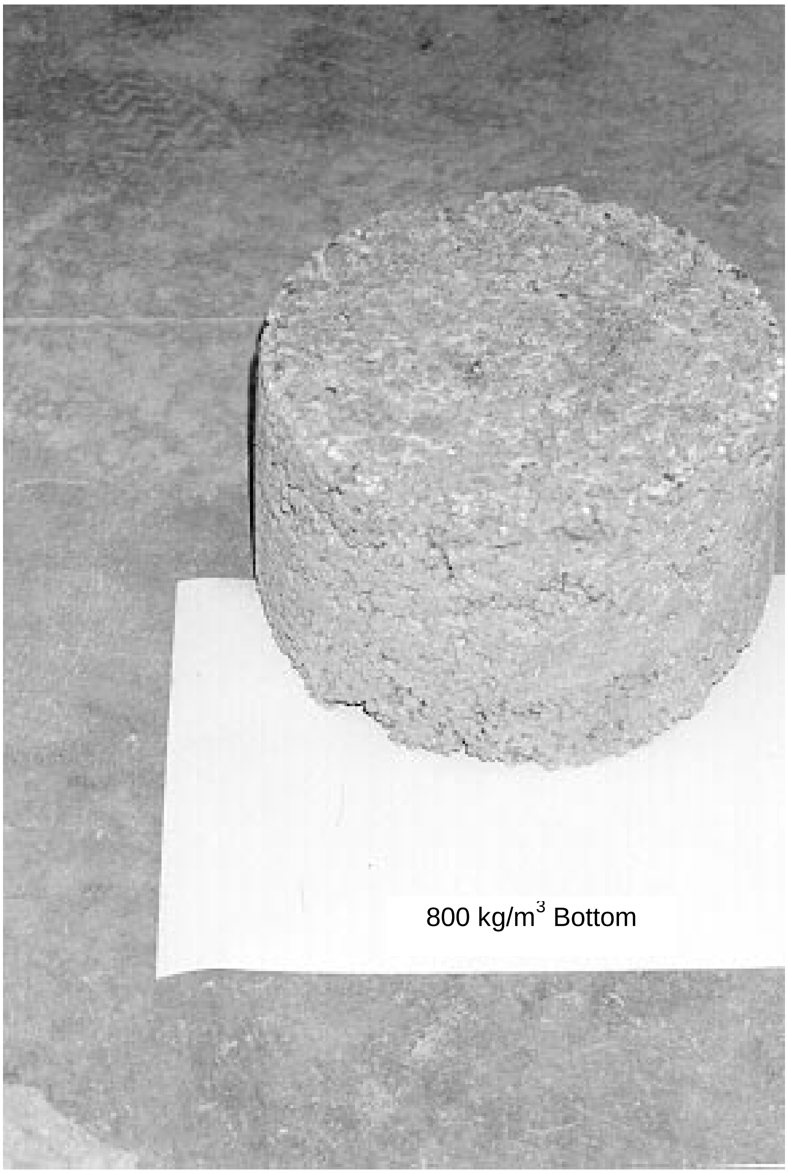

Figure 2. Bottom of the hardened P800 trial mix.

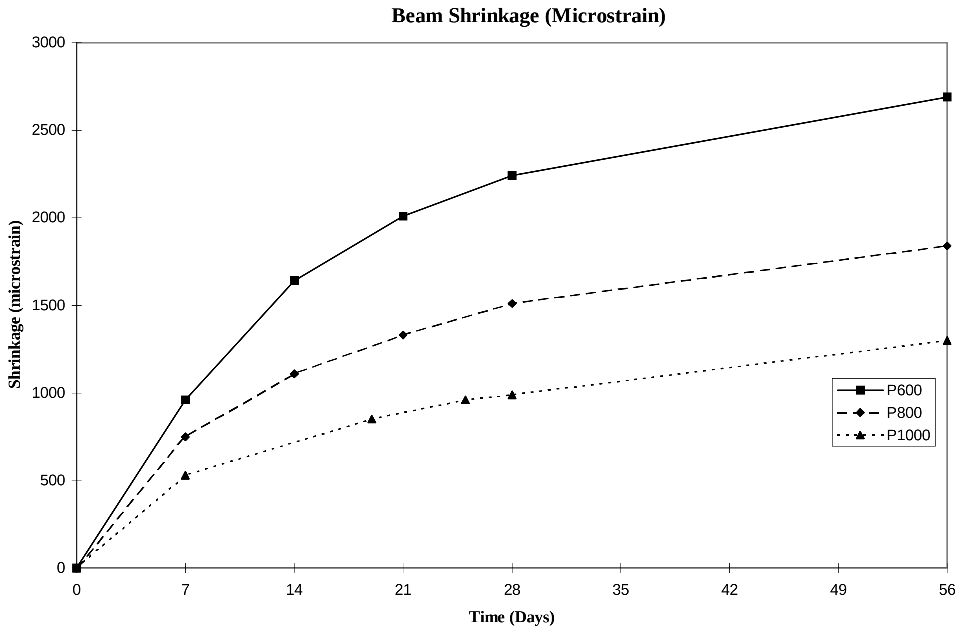

Figure 3. Drying shrinkage of polystyrene aggregate concretes.

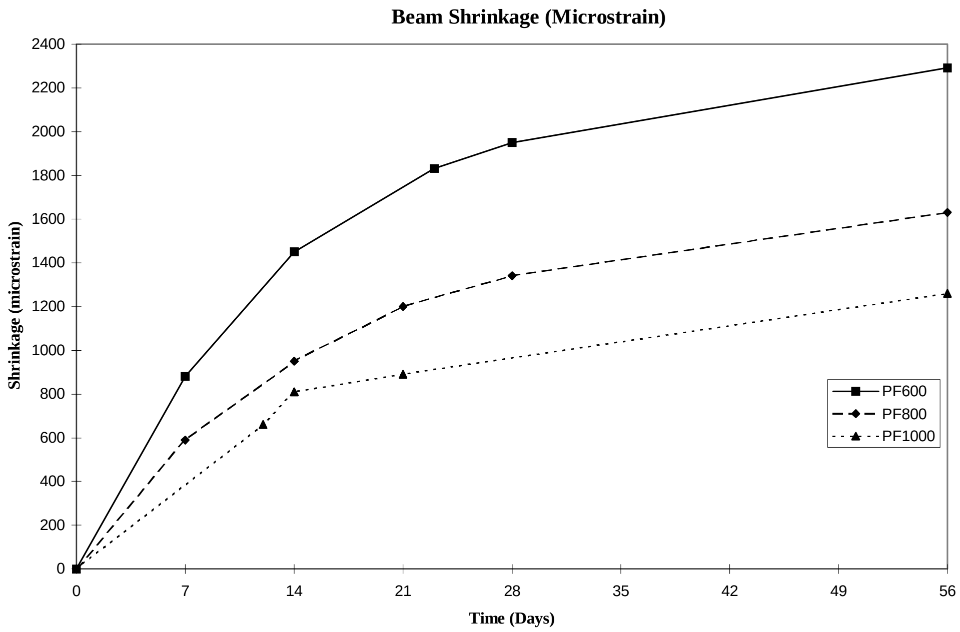

Figure 4. Drying shrinkage of polystyrene aggregate concretes containing fly ash.

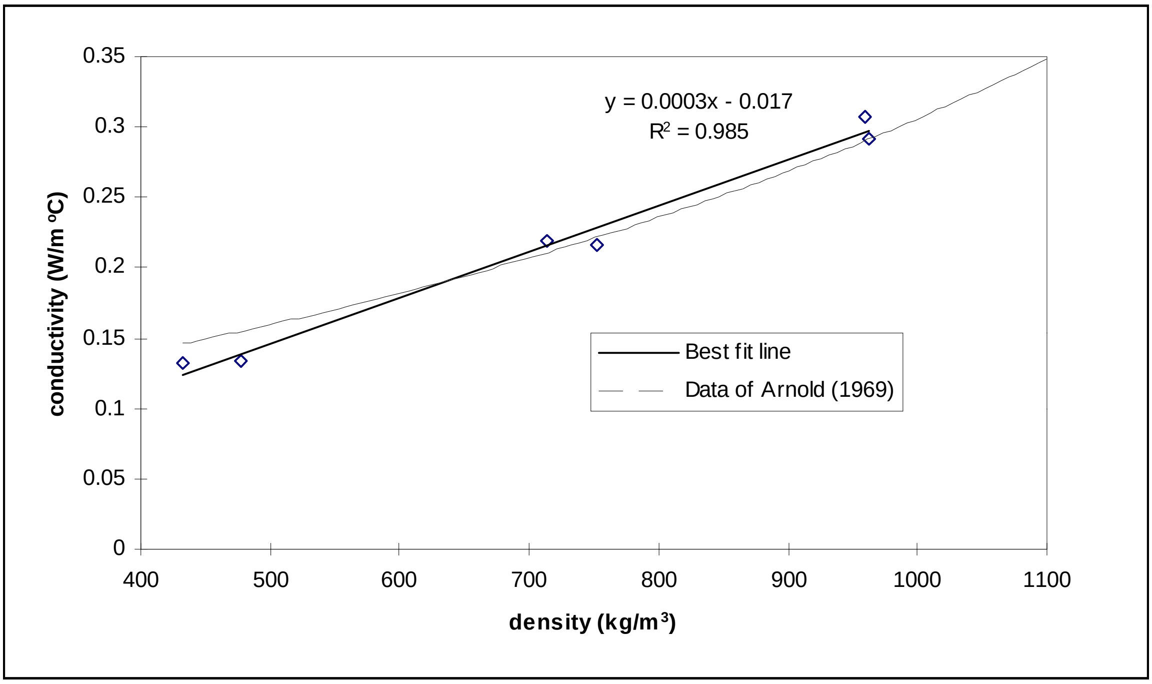

Figure 5. Thermal conductivity of polystyrene aggregate concrete.