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EFFECT OF POROSITIES ON STRENGTH OF PLASTER OF PARIS

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ABSTRACT

Experiments are conducted to study the variation of cube compressive strength, prism flexural strength and cylinder split tensile strength of Plaster of Paris (PoP) specimens with size and with addition of Expanded Polystyrene(EPS) beads, which act as porosities. To study the effect of size, geometrically scaled homogeneous PoP specimens are prepared and the corresponding strengths are determined. To study the effect of porosity, for a fixed volume fraction of EPS beads(V_f), the strength is measured for geometrically scaled specimens of varying sizes. The drop in compressive strength from D=100mm to D=150mm cube specimens is more for V_f=20% as compared to when V_f=0%, 10%. This drop is attributed to change in mechanism of failure from tetrahedral cleavage fracture to distributed parallel cracking. This result progresses the idea of transition from brittle to quasi-brittle material behavior with increase in the porosity under uniaxial compressive loading. In the next study, for a varying volume fraction (V_f = 2%, 5%, 10%, 20%, 30%) of EPS beads, specimens were prepared for a constant cube size of 100 mm and cylinder size of 46 mm diameter. For these specimens, cube compression strength and split tensile strength showed a mild increase followed by monotonic decrease in strength with increasing V_f. The mild increase is attributed to the phenomenon of crack arresting caused by the defects. This result motivates the need for a rigorous theoretical and numerical study for a complete understanding of this phenomenon.

Key Words: *Plaster of Paris, Uniaxial Compression, Brittle to Quasi-Brittle Transition, Porosity, Size-Effect.*

INTRODUCTION

Plaster of Paris(PoP) is a brittle, porous solid, easy to shape, which has potential as a model material for the study of brittle, porous, solids such as ceramics, rocks and cement. The mechanical properties: Youngs Modulus(E), Modulus of Rupture (MOR), fracture toughness (K_{IC}), fracture initiation and yield value under uniaxial compression and hydrostatic compression as a function of porosity were studied by Venkinis et al 1993. In a very recent study by Dong Liu et al 2017 showed that the addition of Expanded Polystyrene (EPS) beads is a reliable way to create additional artificial porosities in PoP specimens. This study carried out four point bending tests on PoP beam of fixed size with varying volume of porosities for a given beam size. In their numerical modeling of bending test, the authors predicted a transition from brittle to quasi-brittle behavior with increase of porosity.

In the current study Arjun S.S. 2017, this transition of behavior from brittle to quasi-brittle behavior with increasing porosity is investigated experimentally for the cases of uniaxial compression tests on cube specimens and split tensile strength on cylinder specimens. The experimental methodology adopts the philosophy of size-effect testing for quasi-brittle materials Bazant et al.,1997.

The experiment program is divided into three phases. In phase one, the size of the cube, cylinder and prism specimens are scaled geometrically and the corresponding compressive strengths for cube and cylinder and bending strengths for prism specimens are measured. In phase two, a fixed volume percentage (volume fraction, V_f) of EPS beads are added to the cube, cylinder and prism specimens of varying sizes and the corresponding strengths are measured. In phase three, specimens of cube and cylinder of given size are cast by varying the volume fraction of EPS beads from 2%-20%. The cube compressive strength and cylinder split tensile strengths are then determined.

RESEARCH SIGNIFICANCE

The experimental program reveals two interesting results regarding the mechanical strength of Plaster of Paris specimens. The first result is compressive strength of cubes undergoes a transition from flaw insensitivity to flaw sensitivity with increase in volume fraction V_f. This inference is deduced from the observed steeper drop in compressive strength for larger size cubes (D=150mm) when compared with smaller size cubes (D=100mm) for larger volume fraction V_f=20% in contrast to V_f=0%,10%. The second result is cube and cylinder specimens showed an increase in their compressive strength and split tensile strength with addition of low volume percentage of EPS beads (V_f=2%), which is counterintuitive.

EXPERIMENTAL PROGRAMME

Preparation of PoP specimen for studying effect of size:

In the first set of experiments, homogeneous PoP specimens of varying sizes are prepared and the strength is determined. For preparing the specimens, the water–POP weight ratio is kept constant at 1:2.

Specimens of 4 different sizes are cast for each of the three shapes namely: cube, cylinder and rectangular prism. Sizes of cubes are 50 mm, 70.7 mm, 100 mm and 150 mm and labelled as C1, C2, C3 and C4 respectively. The cylindrical specimens for compression have a constant length to diameter ratio of 2:1. The diameters are varied as 36 mm, 46 mm, 60 mm, 74 mm and the corresponding specimens are labelled as CY1, CY2, CY3 and CY4. The rectangular prisms used for the flexural tests had length to depth ratio as 3.5:1. The depths are varied as 40 mm, 50 mm, 60 mm, 70 mm and the corresponding specimens labelled as P1, P2, P3 and P4 respectively. These were tested for compression and split-tensile strengths in Universal Testing machine.

For casting cubes, standard steel moulds of available sizes were used. For prisms, plywood pieces were cut into required sizes and joined together by adhesive and made leak proof by using moulding clay. For making cylinders, PVC pipes of various sizes were cut by keeping diameter to length ratio as 1:2 and used as moulds. Plastic sheets were kept inside to prevent POP from sticking to the sides and for easy demoulding.

Preparation of PoP specimens for studying effect of artificial porosities:

EPS beads or expanded polystyrene beads are round in size with diameter ranging from 4-10 mm. These beads are very lightweight and have negligible stiffness. Adding these beads to PoP creates large voids in the PoP specimens. Two case studies were carried out to study the effect of these artificial porosities on the strength of PoP specimens.

Case Study for constant porosity and varying size

To study the effect of porosity on size, 20% EPS beads by volume are added to cube and cylinder specimens. The mixture was prepared as described above and poured into cube moulds of different sizes, viz. 50 mm, 70.7 mm, 100 mm and 150 mm. These were named as A, B, C and D. The specimens were demoulded after 20 minutes and air-dried.

Similarly, cylinder specimens of diameter with 36mm, 46mm, 60mm and 74mm with L/D=2 with V_f=20% EPS beads are prepared. These were named as CY1-20, CY2-20, CY3-20 and CY4-20. All these specimens were tested after 7 days for compressive strength in the Universal Testing Machine.

Case study for varying porosity and constant size

EPS beads are added for the volume fraction value: 2%, 5%, 10%, 20% and 30% to 10 cm cube and 46mm diameter cylinder. Cube compressive strength and split tensile strength are determined for these specimens after 7 days.

For volumes fractions of 30%, 20%, 10%, 5%, 2%, the cube specimens are labelled C1-30, C2-20, C3-10, C4-5, C5-2 and the cylinder specimens are labelled CY1, CY2, CY3, CY4, CY5, CY6. After 7 days, these specimens are tested in Universal Testing Machine(UTM). The peak load and the load-deflection graphs are obtained from UTM for each specimen.

EXPERIMENTAL RESULTS

Effect of size on strength for homogeneous specimen

Three trials of cube compression test for sizes of 5cm, 7cm, 10cm and 15 cm are carried out and the results are shown in table 1a and figure 1.

Two trials of cylinder split tensile strength test for diameters of 36mm, 46mm, 60mm and 74 mm diameter are carried out and the results are shown in table 1b and figure 2. The trial 1 and trial 2 specimens are tested after 7 days.

The four point bending tests are carried out for the specified sizes and the results are tabulated in table 1c and figure 3.

Cylinders are also tested for their compressive strength. The data is shown in table 3d. The plot of compressive strengths of cube and cylinder for trial 3 are shown in the figure 4. For smaller sizes, there is high amount of scatter in compressive strength. For larger sizes, the compressive strength is almost same.

Discussion:

In the cube and cylinder compression tests, steel platens are used to apply the compressive load. The friction present between the specimen and loading platens provide some lateral confinement on the specimens. This confinement resulted in very high values of cube strength for 50mm size specimen (Figure 4). However, as the size of the specimen increased to 100mm and 150 mm, the peak stress at failure is almost similar for the homogeneous PoP specimen. Tests conducted on concrete cube specimens of varying heights 50mm, 100mm and 150mm and constant cross-section of 100mm x 100mm by Van Mier 1984 showed almost constant peak stress with varying post peak slope.

The cylinder specimens showed a decrease in split tensile strength as the size (diameter) of the cylinder varies from 36mm to 70mm for both trial1 and trial 2. This plot of split tensile strength versus diameter(Figure 2) is consistent with Brazilian split-cylinder tests conducted on concrete by Bazant et al.,1991 where the size dependency of strength was observed upto a certain diameter after which the curve of nominal strength versus diameter approaches a horizontal asymptote.

Table 1a: Cube Compressive Strength

S. No.	Cube	Cube Size D(mm)	Compressive Strength(MPa)		
			Trial 1	Trial 2	Trial 3
1	C1	50	7.5	6.68	11.3
2	C2	70.7	6.7	2.99	5.7
3	C3	100	3.9	5.92	5.5
4	C4	150	3.5	4.72	5.3

Table 1b: Cylinder Split Tensile Strength

S. No.	Cylinder	Cylinder Diameter, D (mm)	Split Tensile Strength	
			Trial 1	Trial 2
1	CY1	36	1.76	2.87
2	CY2	46	1.023	2.54
3	CY3	60	0.82	1.54
4	CY4	74	0.92	1.35

Table 1(c) Prism Bending Strength

S. No.	Prism	Dimensions(mm)			Flexural Strength (MPa)
		B=H	L	Span	
1	P1	40	140	120	3.66
2	P2	50	175	150	2.103
3	P3	60	210	180	2.26
4	P4	70	245	210	2.14

Table 1d: Cylinder Compressive Strength

S. No.	Cylinder(L/D=2)	Cylinder Diameter, D (cm)	Compressive Strength(MPa), Trial 2
1	CY1	36	5.26
2	CY2	46	6.23
3	CY3	60	6.1
4	CY4	74	7.775

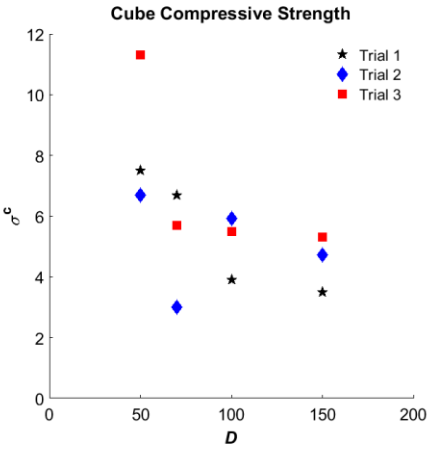

Fig 1: Cube Compressive Strength

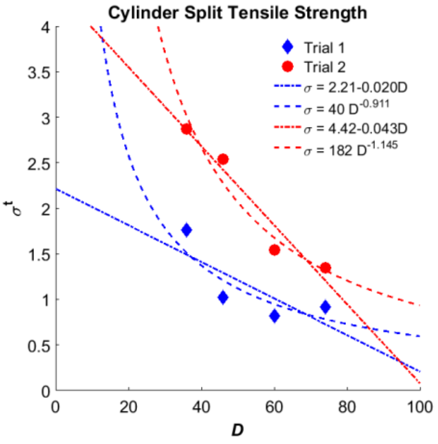

Figure 2: Cylinder Split Tensile strength

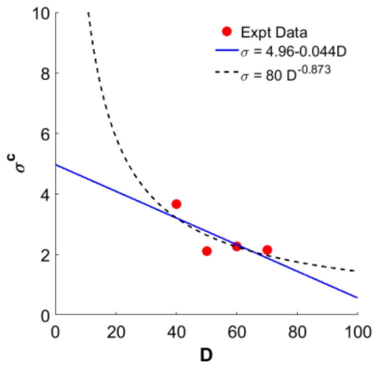

Figure 3 Prism Bending Strength

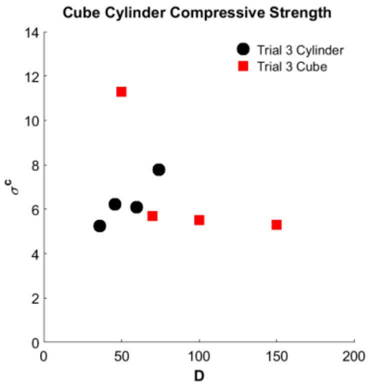

Figure 4: Compressive Strength

Case Study for constant porosity and varying size

Two cycles of cube compression test for sizes of 5cm, 7cm, 10cm and 15 cm with 20% volume fraction of EPS beads and one cycle of 10% volume fraction of EPS beads are carried out and the results are tabulated in table 2a and table 2b.

Discussion: Brittle to Quasi-brittle Transition

The graphical representation of the results as shown in figure 5 is obtained by taking average of the compressive strength for trial specimens tested for V_f=0%, 10% and 20% EPS beads as given in table 1a, 2a, 2b respectively.

The slope of the log σ- log(D) plot for volume fraction V_f = 0% and 10% given as m_0= -0.3056 and m_{10}= -0.185, while for volume of V_f=20% is m_{20}= -1.13 for the specimen size range D=[100mm, 150mm]. This behavior is explained by the looking at the failure mechanism taking place under compressive loading. For V_f =0%, the failure surface developed as tetrahedral cleavage as shown in figure 3a. For V_f=20% the cracking was distributed throughout the specimen for the 100mm and 150mm specimens as shown in figure 3b. This transition in failure mechanism resulted in more drop in compressive strength from 100mm to 150mm for V_f=20% .

The idea of quasi-brittle behavior where the fracture process zone occupies non-negligible volume is well studied for tensile loading in literature (refer figure 3c). In compressive loading, homogeneous material exhibits brittle behavior. The addition of porosities results in formation of micro-cracks in regions where stress concentration factor is high. This zone of micro-cracking increases as the volume fraction of porosities increases. Hence, the transition from brittle to quasi-brittle behavior occurs with increase in porosity (refer figure 3d).

Table 2a: Cube Compressive Strength for 20% volume fraction of EPS beads

SL. NO.	CUBE SPECIMEN	% VOLUME FRACTION OF EPS	% WEIGHT LOSS		COMPRESSIVE STRENGTH (MPa)	
			Trial 1	Trial 2	Trial 1	Trial 2
1.	A: 5cm	20	25.9	24.57	2.52	3.7
2.	B: 7cm	20	26.0	25.19	5.4	4.3
3.	C:10cm	20	24.5	22.71	5.26	4.0
4.	D:15cm	20	21.2	25.32	2.82	2.98

Table 2b: Cube Compressive Strength for 10% volume fraction of EPS beads

SL. NO.	Trial 1 Cube Specimen	% VOLUME FRACTION OF EPS	% WEIGHT LOSS	COMPRESSIVE STRENGTH (MPa)
1	A: 5cm	10	27.27	4.38
2	B: 7cm	10	27.13	5.43
3	C:10cm	10	27.97	3.82
4	D:15cm	10	25.93	3.54

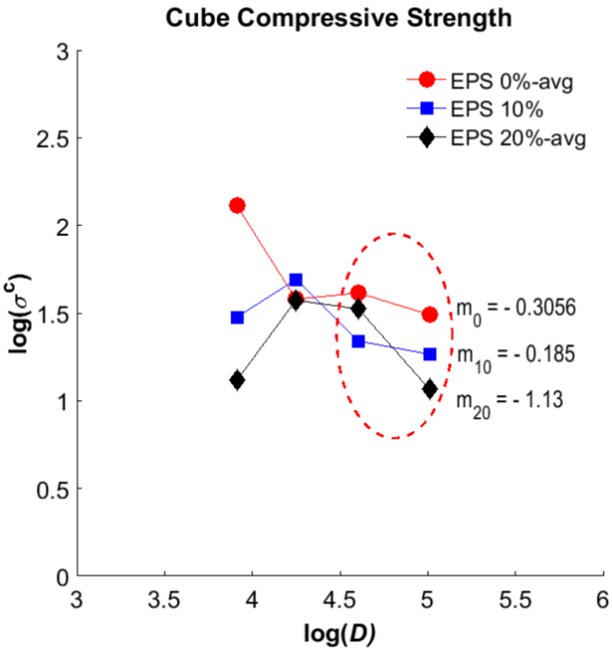

Figure 5: Cube Compressive Strength for V_f=0%, 10%, 20%

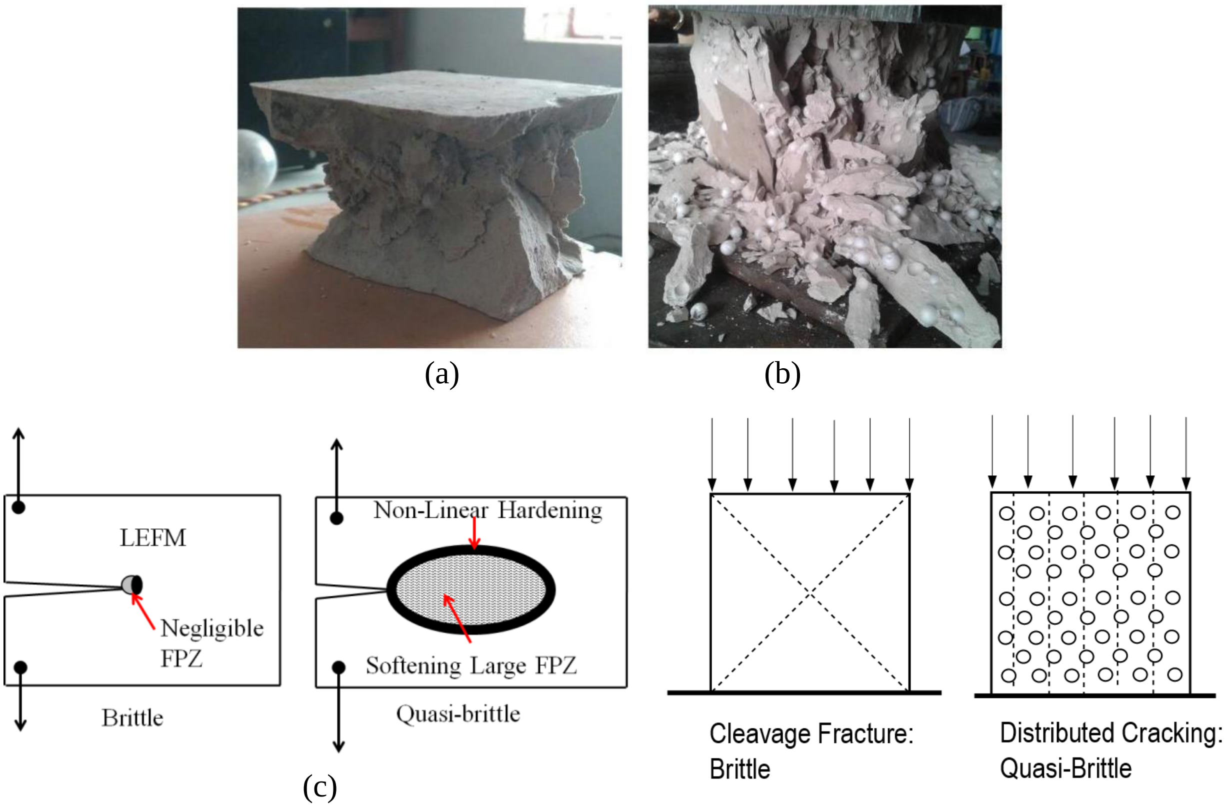

Figure 6: a) Cleavage fracture b) Distributed cracking c) Tensile Loading d) Compressive Loading

Case Study for varying porosity and constant size

Two sets of 10 cm cube specimens are cast by varying the volume fraction of EPS beads from 0%-30%. These cubes are tested after 7 days. The results of these tests are listed in Table 3. The graphical plot of the compressive strength versus volume fraction is shown in figure 7.

46 mm diameter cylinder specimens are cast by varying the volume fraction of EPS beads from 0%-30%. These cylinders are also tested after 7 days. The results of these tests are listed in Table 4. The graphical plot of split tensile strength versus volume fraction of EPS beads is shown in figure 8.

Discussion

Both the compressive strength and split tensile strength increase with addition of low volume fraction of EPS beads (V_f = 2%, 5%) as seen in figures 7 and 8. This behavior could be due to crack arresting exhibited by the randomly distributed spherical voids as described in Ling Liu et al., 2008. Further addition of EPS beads leads to a monotonic drop in compressive strength and split tensile strength. A complete understanding of this behavior requires a three dimensional numerical simulation, which is beyond the scope of the research conducted in the present study.

Table 3: Compressive strength of 10 cm cube for varying volume fraction of EPS beads

SL. NO.	10 cm Cube Specimen	Percent Volume Fraction of EPS	% Weight loss		Compressive Strength (MPa)	
			Trial 1	Trial 2	Trial 1	Trial 2
1.	C1-30%	30	23.9	19.9	3.6645	1.135
2.	C2-20%	20	24.5	23.4	5.2595	4.005
3.	C3-10%	10	22.7	18.3	7.3445	6.150
4.	C4-5%	5	23.7	24.8	6.5595	8.485
5.	C5-2%	2	24.0	24.3	3.4245	10.12
6.	C6-0%	0	--	25.4	- - -	9.81

Table 4: Split Tensile Strength of 46mm cylinder for varying volume fraction of EPS beads

SL. NO.	Cylinder Specimen, 46mmΦ	% Volume Fraction of EPS	% Weight loss	Split Tensile Strength (MPa)
			Trial 1	Trial 1
1.	CY1A-30%	30	27.63	0.5792
2.	CY2A-20%	20	27.62	0.6544
3.	CY3A-10%	10	26.61	0.9101
4.	CY5A-2%	2	27.34	0.9928
5.	CY6A-0%	0	25.70	0.8349

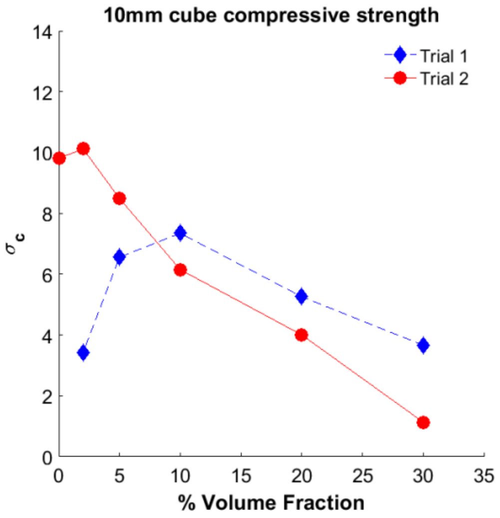

Figure7: Compressive strength of 10cm cube for varying volume fraction of EPS beads

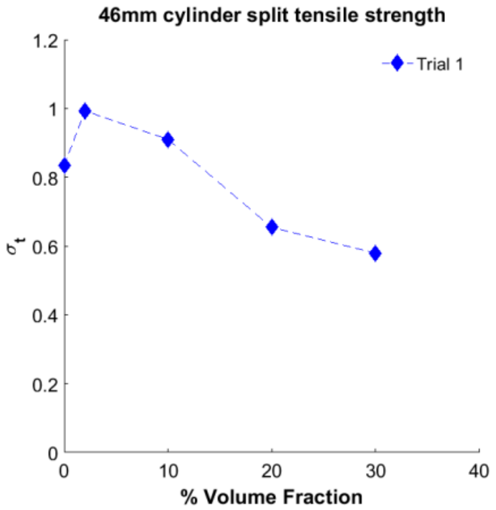

Figure 8: Split Tensile Strength of 46mm cylinder for varying volume fraction of EPS beads

CONCLUSIONS

1. Cube compression tests on Plaster of Paris specimens showed large variation in strength at smaller sizes. For higher sizes, the variation in strength is very low.
2. The split-tensile strength also exhibited a downward trend with increase in size and the curve of stress versus size reaches a horizontal asymptote.
3. EPS beads create artificial voids in the PoP specimens. With the gradual increase in volume fraction of EPS beads, there is a transition in compression failure mechanism from cleavage cracking to distributed cracking. This resulted in higher drop in compressive strength for cubes with higher EPS volume fraction when the size increased from 100mm to 150mm.
4. Addition of low volume fraction of EPS beads to PoP specimens resulted in higher compressive strength for 100mm cube and higher split tensile strength for 46mm cylinder. These higher strengths are attributed to the crack arresting caused by voids. A rigorous theoretical and numerical study is needed to get a complete understanding of this phenomenon.

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