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Deformation Behaviour of Rock around a Borehole Filled with an Expansive Cement

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ABSTRACT. The use of commercially available expansive cement as a demolition agent and for rock breakage in populated areas and dimension stone quarries is on the increase. It is extensively used in Saudi Arabia for rock fracture in urban areas as well as granite and marble quarries.

An attempt is made to study the deformation behaviour and fracture of hard rocks like granite when subjected to a slowly increasing expansive pressure exerted inside a borehole filled with an expansive cement by the measurement of tangential strains at various points around it. The effect of variation of burden (minimum distance of the hole from the nearest edge) and borehole diameter is also investigated.

1. Introduction

Fracturing of rocks with expansive materials has been practiced by people through the ages. One of the methods was comprised of pouring quicklime into the cracks/fissures in big boulders and enlarging them by the expansive property of hydration and finally breaking them with the help of wooden wedges[1]. The use of expansive cements as a substitute for explosives is on the increase, specially in non-violent and pollution-free breakage of rocks in populated areas and in dimension stone quarries where excellent control on breaking rocks to the required dimensions is achieved. Two Japanese manufacturer, namely, Onada Cement Company and Sumitomo Cement Company are marketing expansive cements in Saudi Arabia under the trade names of Bristar and S-mite, respectively. Recently one local manufacturer, FOSAM has started marketing an expansive cement under the brand name of Fosroc.

Bristar, the most popular brand, is basically supplied in four grades as Bristar-100, 150, 200 and 300, suitable for use in maximum allowable temperature of 35°C, 20°C, 15°C and 5°C, respectively. Lately Bristar-100S is supplied as being more suitable than Bristar- 100 for the temperature conditions of Saudi Arabia[2].

Onada Cement Company[2] carried out research on the properties of various grades of Bristar expansive cement using long, thin-walled steel cylinders with strain gauges glued to their exterior for the determination of expansive pressure generated by the cement. They found out that a stress level of 1300 t/m^2 to 3200 t/m^2 was achieved with the internal diameters of 10 mm and 50 mm, respectively. Shiro Ishii[3] reports that Bristar basically consists of lime, clay and gypsum which are mixed in a certain proportion and burnt in a rotary kiln at 1500°C. The resulting clinker is ground to 2000 to 3000 cm^2/g specific surface area of grains.

Dowding and Labuz[4] used thick walled steel cylinders for determining the internal pressure exerted by Bristar expansive cement. They used strain gauges at one of the faces and the external cylindrical surface to measure tangential tensile strain, wherefrom, they calculated internal pressure using elastic solution of stresses and strains on thick walled cylinders[5-7]. Dowding and Labuz[4] have indicated that the expansive pressure is not a function of the borehole diameter and, therefore, a simple scaled distance relationship of borehole spacing and diameter is appropriate for relating tests with different hole diameters in the same material. They noted that temperature and thermal sensitivity could influence the spacing. They also performed tests on dolomite rock and found out that the removal effort was optimized with a spacing of 8 borehole diameters.

Dar *et al.*[8] carried out research to determine the optimum burden to spacing ratio for the use of Bristar-100 expansive cement in the marble quarries of Saudi Arabia. They conducted laboratory tests on a marble block using various combinations of burden and spacing with 14 mm diameter holes and correlated the laboratory results with those of the field trials in a marble quarry with 34 mm diameter holes and also scaled thick-walled steel cylinders with strain gauges for determining pressure generated in the holes. In all the cases it was found that the pressure generated by Bristar-100 expansive cement, mixed with 30% by weight of water generated a pressure of the order of 40 MN/m^2 after 52 hours of pouring. This pressure is far greater than the tensile strength of most rocks. They also found that a burden to spacing ratio of 0.8 gave the best results for the optimum use of Bristar-100.

In order to extend the scope of the research to hard dimension-stones (like granite) quarries, a research project was undertaken by Darwish and Hanif[9] with the following objectives :

1) To determine the strain-time relationship at various points around a borehole filled with an expansive cement and stury the propagation of cracks.

2) To determine the optimum bore-hole spacing, burden and depth for the optimum use of expansive cement in hard dimension-stone (like granite) quarries of Saudi Arabia.

The paper reports the first part of the research which involved laboratory tests on a granite block from Widd quarry near Taif, measuring 1.0 m × 0.6 m × 0.6 m. One of the 1.0 m × 0.6 m faces saw cut and ground. A 14 mm diameter hole was drilled to a depth of 260 mm at distance of 112 mm from two adjacent edges and a number of strain gauges were tangentially fixed at various distances and at different angular positions. Bristar-100S expansive cement was mixed with an appropriate proportion of water and poured in the borehole. Periodic readings of all the strain gauges were taken. In order to investigate the effect of borehole diameter the experiment was repeated at another point with burden increased to 220 mm and the 14 mm diameter hole was successively reamed to 20 mm and 25 mm diameter.

2. Testing of Widd Granite for Mechanical Properties

The expansive cement, when mixed with water and poured into a borehole, causes radial compressive and tangential tensile stresses in the surrounding rock mass. Since the rocks are much weaker in tension than compression, the tensile strength is the most important property in determining whether or not a rock will break. Equally important are the elastic properties like Poisson's ratio and Young's modulus. Shear strength too becomes important in certain instances. It would also be interesting to determine the uniaxial compressive strength.

The Brazilian test, point load test and flexure (beam) test were made to indirectly determine the tensile strength of rock. The punch shear test was employed to determine the rock shear strength. The uniaxial compression test and stress-strain behaviour test were conducted on 35 mm diameter and 70 mm long specimens. The latter test was employed for the determination of Young's modulus and Poisson's ratio.

The Brazilian test was conducted by applying a diametral line load on discs cut from the 35 mm diameter core. If *P* is the applied load at failure; *d*, the diameter and *L*, the thickness of the disc, then Brazilian tensile strength T_B is given by

$$T_B = \frac{2\,P}{\pi\,d\,L}$$

The point load test involves compression of a specimen between two hardened spherical points. It was originally developed by Brock and Frankline[10] for application on unprepared lump specimens and has been extensively used for strength logging of diamond drill cores of rocks[6,7,11]. The point load tensile strength index T_{dp} was given by

$$T_{dp} = \frac{P}{d\,L}$$

In flexure (beam) test, 35 mm diameter cores of the rock were subjected to 3-point loading. The values of modulus of rupture, thus determined, were 2.5 to 3 times greater than the Brazilian tensile strength values.

The punch shear test was performed on 35 mm diameter discs and nominally 7 mm thick polished discs cut from the core. The punch diameter was 15 mm. The punch shear strength, s, is given by

$$s = \frac{P}{\pi\, d\, L}$$

where P is the load at failure, d is the punch diameter and L is the disc thickness.

For uniaxial compression test, cylindrical specimens of 35 mm diameter and 70 mm nominal length were prepared by cutting and grinding the ends smooth and parallel. In all the cases the specimens failed by radial tensile splitting suggesting a perfect brittle failure.

The stress-strain behaviour test was performed on two specimens having a diameter of 35 mm and nominal length of 70 mm. Four strain gauges were glued to each specimen; two in the axial direction and two in the lateral direction. The two sets of gauges for each specimen were fixed on opposite sides of the cylindrical surface for a better averaging of the measurements. The strains were measured by the use of a digital strain indicator and a 10-channel switching and balancing unit. The mean values of the axial and lateral strains for each increment of load were taken. Figure 1 shows a typical stress vs. strain relationship.

A summary of test results on Widd granite is presented in Table 1.

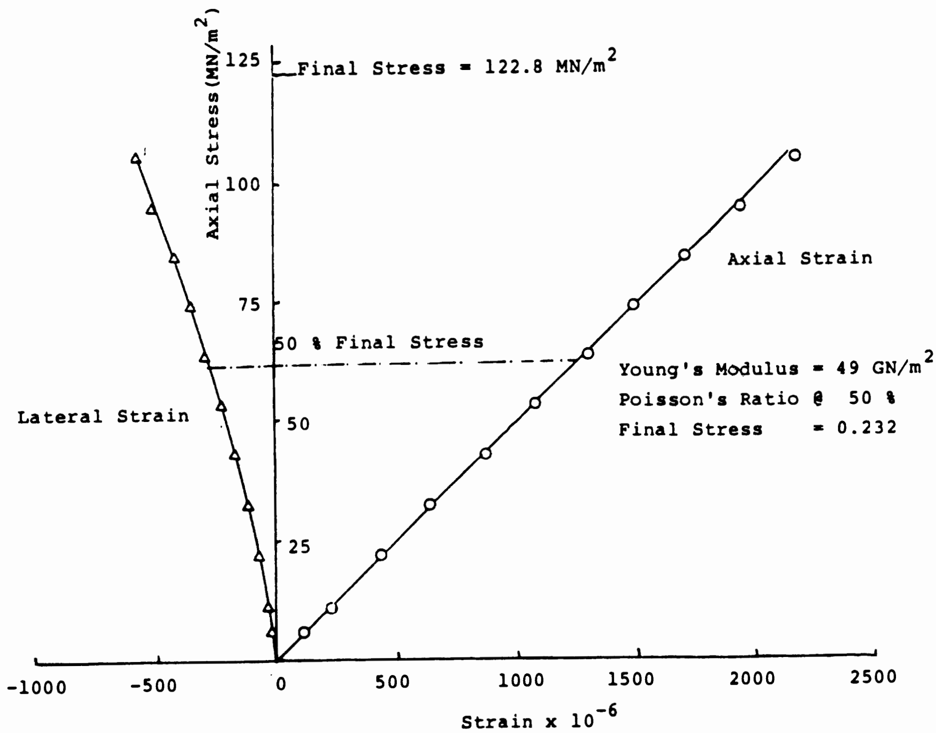


FIG. 1. Stress-strain relationship for specimen no. 2.

TABLE 1. Summary of test results performed on Widd granite.

No.	Test	Parameter	Result
1	Brazilian test	Indirect tensile strength (mean of 12 measurements)	6.70 MN/m^2
2	Point load test	Tensile strength index (mean of 14)	7.71 MN/m^2
3	Punch shear test	Shear strength (mean of 7)	23.78 MN/m^2
4	Uniaxial compression test	Uniaxial compressive strength	127.0 MN/m^2
5	Stress-strain behaviour test (3 tests)	Young's modulus (Secant @ 50% final stress) Poisson's ratio (@ 50% final stress)	50.2 GN/m^2 0.235

3. Measurement of Strains around a Borehole Filled with an Expansive Cement

A 1.0 m × 60 cm × 60 cm block of granite from Widd quarry near Taif was obtained, one rectangular face (1.0 m × 60 cm) of which was saw cut and polished for the ease of installation of strain gauges in one plane.

It was aimed to drill a hole at an appropriate distance from the edges of the polished surface and to install a number of strain gauges around the borehole in order to establish the strain vs. time pattern around the borehole when an expansive cement was mixed and poured inside it and the strain gauges were periodically monitored over an appropriate period of time. It was intended, then, to enlarge the hole and repeat the experimental procedure twice in order to record the effect of borehole diameter on strains produced.

Experiment No. 1

A fourteen millimeter diameter and 260 mm deep hole was drilled normal to the polished surface at a distance of 112 mm from two adjacent sides. This distance was arrived at by experienece with marble and application of the following scale relationship

$$\frac{E_g\,(r_{og}^2 - r_{ig}^2)}{r_{ig}^2} = \frac{E_m\,(r_{om}^2 - r_{im}^2)}{r_{im}^2}$$

where subscripts g and m refer to granite and marble, respectively and E, r_o and r_i represent Young's modulus, outside radius and inside radius of a thick cylinder, regarding the radius of the borehole as r_i and the smallest distance between the centre of the hole and the edge of the block (burden) as r_o .

Young's modulus of Widd granite was determined as 50.2×10^9 N/m^2 compared with 34.8×10^9 N/M^2 for marble block on which tests were performed by Dar *et al.*[8]. The distance of 112 mm for the granite would be equivalent to 133 mm for marble.

Hanif[12] developed the following rock strength similarity number, N_R based on the criterion of tensile strain due to compression

$$N_R = \frac{F\,v}{L^2\,T_o}$$

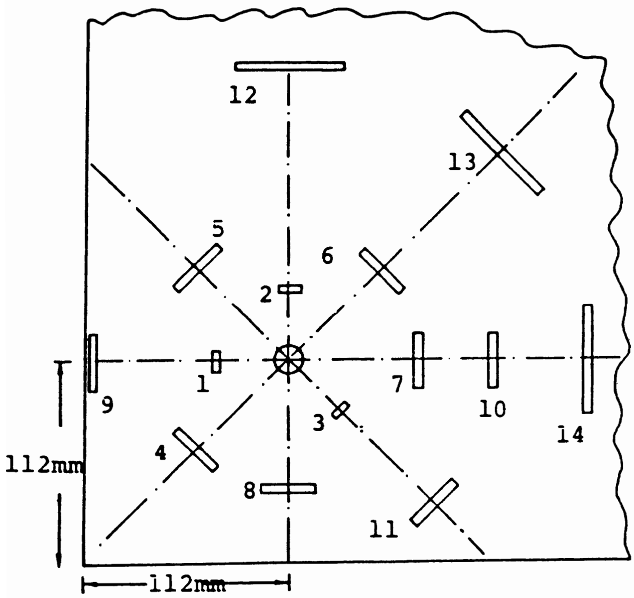
where F is the force on a system, v is Poisson's ratio, L is any linear dimension and T_o is the tensile strength.

Thus for the similarity of Widd granite and marble with their respective tensile strengths of 6.70 MN/m^2 and 6.55 MN/m^2[8] and Poisson's ratios of 0.24 and 0.30[8], using the following relationship

$$\frac{F_m\,v_m}{L_m^2\,T_{om}} = \frac{F_g\,v_g}{L_g^2\,T_{og}}$$

we obtain spacing value of 118 mm for granite as equivalent to 133 mm for marble. However, distance 112 mm was used according to the first criterion.

Fourteen strain gauges were glued on positions indicated in the Fig. 2. The strain gauges were positioned with respect to 8 radial lines having an angular difference of 45° and to 4 sets of distances from the center of the borehole.



Gauge	Gauge length (mm)	Radial distance (mm)
1	12	40
2	12	40
3	12	40
4	25	70
5	25	70
6	25	70
7	25	70
8	25	70
9	25	110
10	25	110
11	25	110
12	60	160
13	60	160
14	60	160

FIG. 2. Positioning of strain gauges around 14 mm dia. borehole.

Except for the three outermost 60 mm long gauges which were of wire type, the rest were all of constantin alloy. Measurements of strain were made with a digital strain indicator having at least count of one micro strain. A half-wheatstone bridge circuit using a dummy gauge for each active gauge was employed. Prior to the commencement of the test, the gauges were connected to the strain meter and monitored for about a week in order to determine the creep behaviour of each pair of gauges connected to its specific channel.

The test was started by pouring Bristar-100S thoroughly mixed with 30% by weight of water as recommended by the manufacturer.

Table 2 gives the creep-corrected strains at various times. Figure 3 shows corrected values of strain measured at selected points and at different times.

TABLE 2. Strains around 14 mm dia. hole filled with Bristar-100S expansive cement (Exp. 1).

Strain gauge no.	Creep-corrected strain $\times 10^{-6}$ after hours :																
	5	9	11	18	24	30	48	57	67	73	81	92	96	168	192	216	240
1	12	18	27	65	68	79	127	162	206	221	246	285	293	490	545	552	569
2	8	31	57	88	114	131	212	260	319	347	388	445	463	802	794	887	701
3	7	26	35	81	92	101	139	157	187	200	217	241	246	362	383	393	446
4	10	35	37	50	56	65	63	63	98	93	84	85	96	113	107	39	37
5	8	16	13	40	38	38	54	66	75	90	93	101	105	166	190	109	85
6	4	12	14	24	31	35	44	47	53	55	56	59	59	86	96	106	103
7	10	22	28	45	48	50	61	63	75	77	78	82	82	106	112	111	118
8	6	18	24	46	52	59	78	86	101	107	114	129	132	360	694	Cracked	
9	–	–	Inconsistent readings (Faulty strain gauge)														
10	2	6	10	18	18	19	24	24	30	31	31	33	32	39	40	30	28
11	–	–	Inconsistent readings (Faulty strain gauge)														
12	0	1	2	4	2	4	7	8	10	11	11	13	11	27	35	69	–
13	0	1	3	7	7	8	12	9	15	14	13	14	14	22	25	32	37
14	0	1	7	9	7	5	7	7	16	17	11	10	16	20	19	17	15

Experiment No. 2(a)

Since the rock in Experiment no. 1 was cracked before the hole diameter could be enlarged, the burden for the second test was nearly doubled at 220 mm.

A fourteen millimeter diameter hole was drilled to a depth of 260 mm. A total of 12 strain gauges were installed according to the plan in Fig. 4. All strain gauges used for this experiment were wire type, which were found to be less susceptible to creep than the foil type gauges. The gauges were of 30 mm and 60 mm gauge length. Figure 5 shows for the results of strain gauges at selected positions.

Experiment 2(b)

After 5 days, Bristar from the 14 mm borehole was drilled out and the hole was

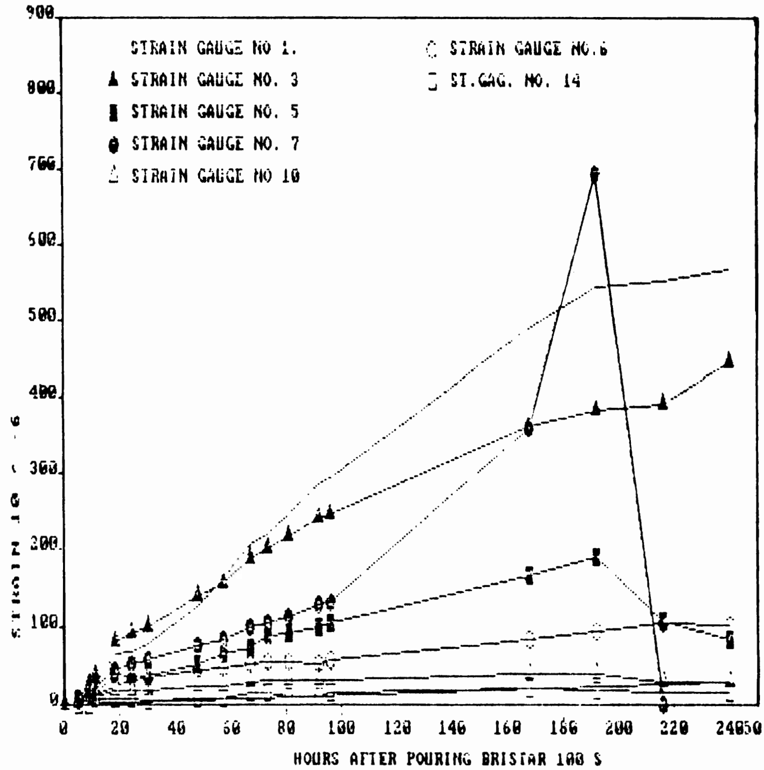
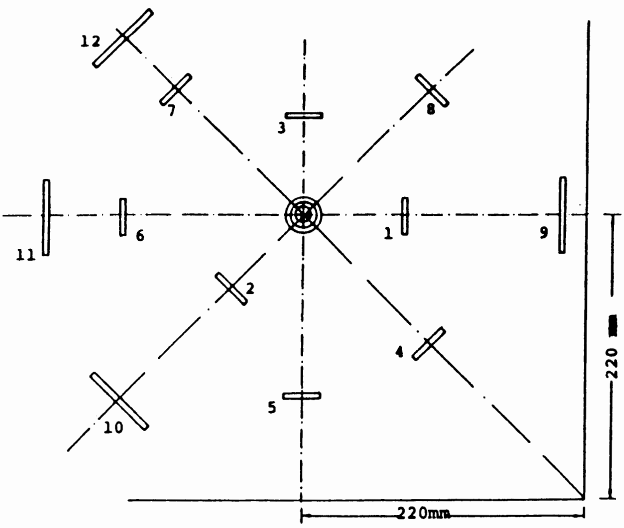


FIG. 3. Time strain graph for some of the strain gauges for Experiment No. 1.



Strain gauge no.	Gauge length (mm)	Distance from hole (mm)
1	30	80
2	30	80
3	30	80
4	30	140
5	30	140
6	30	140
7	30	140
8	30	140
9	60	200
10	60	200
11	60	200
12	60	200

FIG. 4. Positioning of strain-gauges for experiment no. 2 (a, b and c).

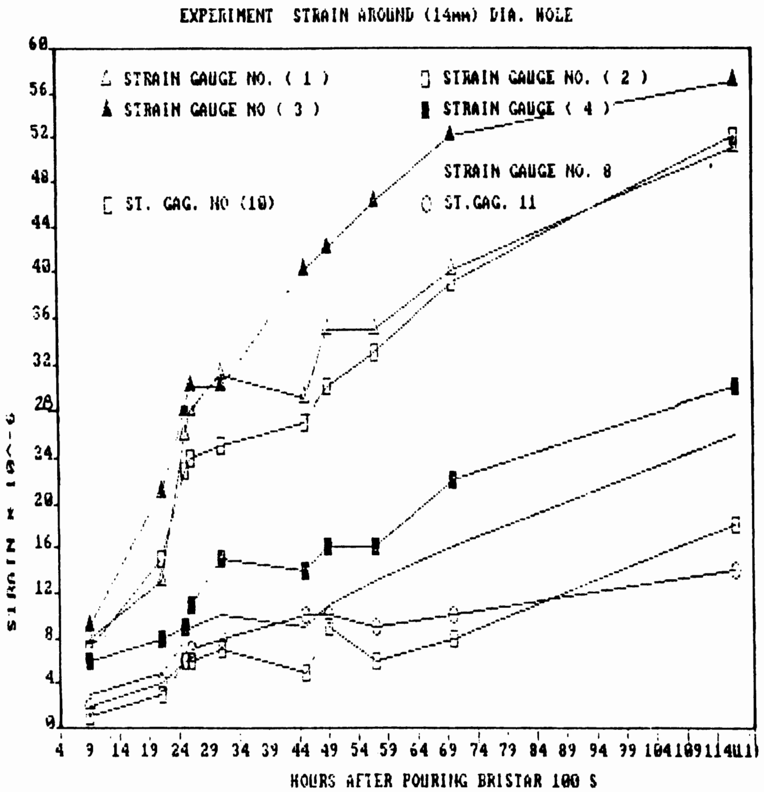


FIG. 5. Strain-time graphs for some of the strain gauge for experiment 2 (a).

reamed to 20 mm diameter. Bristar was again poured in the 20 mm borehole and periodic measurements of strains were made. The results of these measurements for selected strain gauges are shown in Fig. 6. This process was continued for 172 hours, Bristar was then drilled out.

Experiment 2(c)

The hole was again reamed to 25 mm diameter and strains were periodically monitored. A hairline crack was noticed on one side of the hole after 50 hours. The crack propagated to the other side of the hole at 70 hours and extended right across the block. Figure 7 shows the strain-time graph for some of the strain gauges.

Figure 8 shows the position of the two cracks resulting from the two experiments. The position of the crack resulting from Experiment 1 appears to be quite logical. However, the position of the crack related to the second test, being parallel to the crack of Experiment 1, may be due to a slight parallelism of the rock grains.

Discusion of Results

1. The ratio of tensile (Brazilian test) strength for Widd granite to its uniaxial compressive strength was 1:19. This seems to be typical of a coarse crystalline,

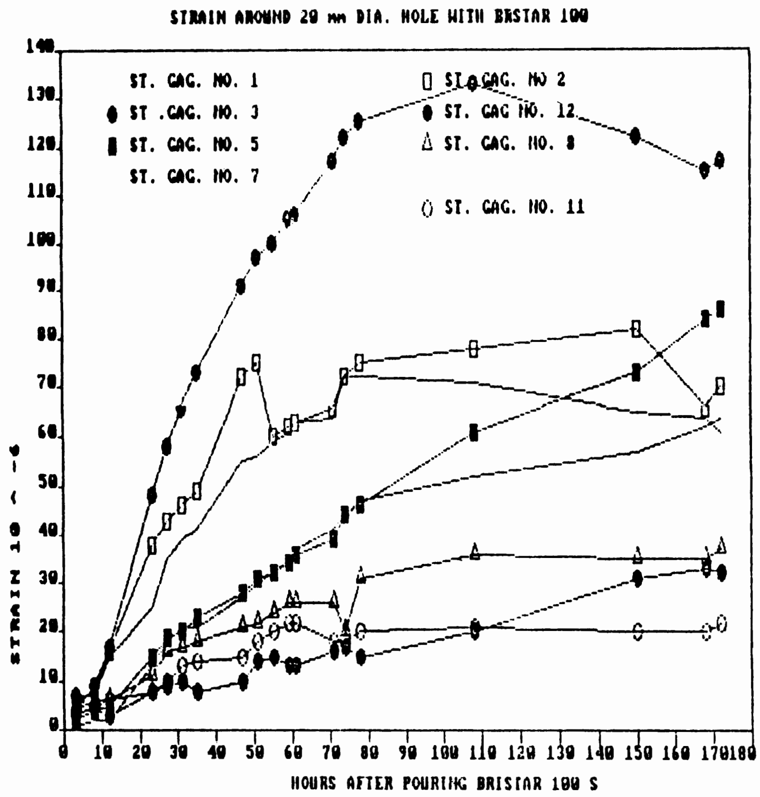


FIG. 6. Strain-time graph for some of strain gauges for Experiment 2(b).

heterogeneous rock like granite.

2. The axial stress versus axial strain curves for all the three tests were linear with only a slight reduction in slope close to the failure point suggesting that Young's modulus of elasticity would remain practically the same. The axial stress versus lateral strain curves were, however, not linear, suggesting that the value of Poisson's ratio would increase with the increase in stress.

3. Some of the results yielded by Experiment no. 1 were as follows :

i) In general, the strain gauges close to the borehole registered greater strains than the ones farther off.

ii) The rate of increase of strain (slope of strain vs. time curves) was, in general, constant until 18 hours after pouring the expansive cement. It then abruptly decreased but, later, gradually increased. The abrupt fall in rate of increase of strain may be explained by a probable outward slippage of the cement in the vicinity of the collar. The rate of increase of strain again picked at 30 hours and was almost constant until 96 hours. Between the 96*th* hour and 168*th* hour, all strain gauges registered increase. Strain gauge (SG) no. 2, then, registered decrease while SG 8 and 12 registered unusual increase and, then decreased down to zero as a hairline crack was noticed. SG 4, 5, 10 and 14 registered significant decrease while SG 1, 3, 6, 7 and 13

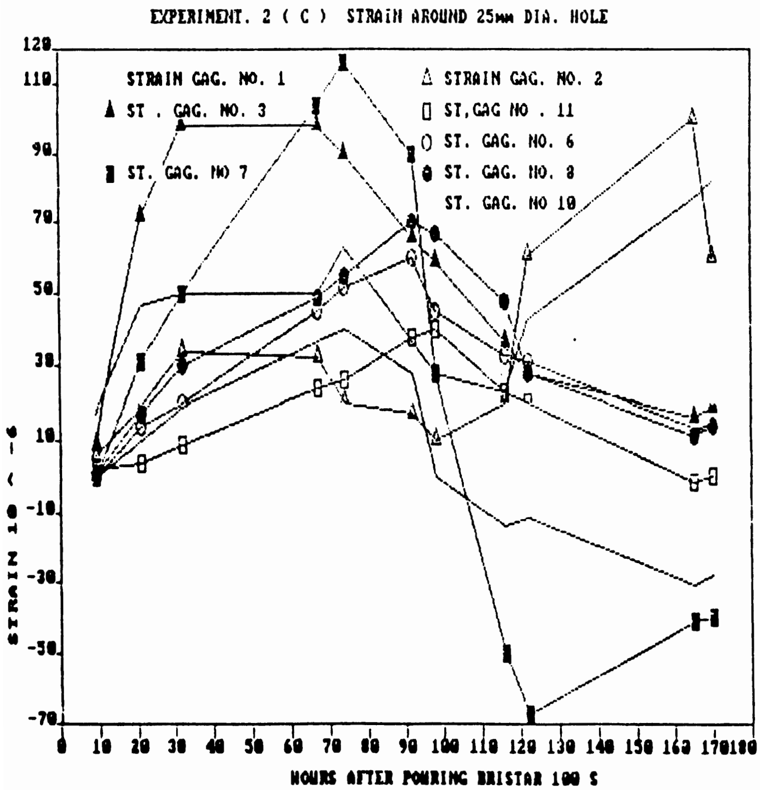


FIG. 7. Strain-time graph for some of the strain gauges for Experiment No. 2(c).

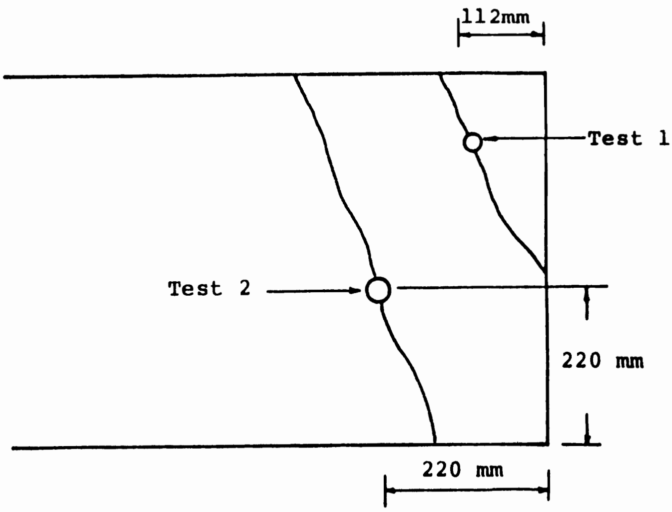


FIG. 8. Experiment 2(c); extension of crack to other side of the hole after 70 hours.

continued to increase.

It would be evident from these observations that an event affects all the strain gauges, albeit differently, which may be explained by a readjustment of the stresses at various points around the borehole. This is manifested by a variation of the rate of change of strains at those points.

Prior to an imminent failure, the slope of strain vs. time curve continues to increase until the appearance of a crack. This phenomenon, however, occurs only at critical points; as demonstrated by the readings in SG 7 and to a lesser extent in SG 2 and 11.

4. The results of Experiment 2(a) are plotted in Fig. 5. The abrupt variations in most of the curves up to 57 hours may be due to the slippage of the cement close to the collar. In general the strains continued to increase in all the strain gauges until the cement was drilled out after 117 hours. The level of strain in all the gauges was much lower than in Exp. 1. The mean of three strains at 80 mm from the centre was 53 micro-strains after 117 hours while the mean of readings of 5 gauges at 70 mm from the centre for Exp. 1 was 102 (computed) micro-strains over the same period of time. This may be explained by the increased burden which was doubled in Exp. 2.

5. Experiment 2(b) with 20 mm borehole, indicated a consistent increase in the strain recorded for all the gauges until 51 hours when SG 2 registered a fall but picked up again. After 78 hours, most of the strain-time curves levelled off, while one actually sloped downwards. The downward trend worsened at 108 hours suggesting that the failure might have actually taken place around 78 hours after pouring. No visible crack was, however, noticed until 172 hours, when the cement was drilled out and the hole was reamed to 25 mm diameter for Exp. 2(c). A comparison of the results of Experiments 2(a) and (b) would reveal that the rate of increase of strain was larger for the larger diameter.

6. Figure 7 shows some of the strains plotted for Exp. 2(c). All the strain-time curves increased quite fast until 32 hours, when strains at the three innermost locations levelled off or actually decreased, while the others continued to increase. A crack was noticed at 50 hours on one side of the hole. This indicated that the crack would have actually initiated around 32*nd* hour. Some of the gauges registered another sharp decrease at 67 hours. This event may be related to the extension of the fine crack on the other side of the hole at 70*th* hour. All the curves slided downwards somewhere between 67 and 122 hours coinciding with the widening of the crack. In the process, some of the gauges finally registered negative values which may be, at least partly explained by a possible difference in the stress distribution caused by the breakage of the block.

Conclusion

A. Conclusion related to rock testing

1. The tensile to compressive strength ratio to Widd granite was 1:19, which is characteristic of coarsely crystalline granitic rocks.
2. The values of Point load and Brazilian strength were fairly close to each other.
3. The values of Young's modulus for Widd granite would be practically constant

except for a slight decrease close to the final stress. The value of Poisson's ratio, however, was found to increase with an increase in stress.

B. Conclusion related to strains measurement around boreholes filled with the expansive cement

1. Tangential strains closer to the hole were greater than the ones farther off from the holes.
2. Strains generally increased with time until failure.
3. A readjustment of strain rates at various points occurred at the time of deformational events such as the appearance of a crack. The occurrence of inconspicuous cracks can be inferred by an anomalous decrease of strain rate at some of the points.
4. For the same diameter (14 mm), the strain rate was much greater for a smaller burden than for a greater burden.
5. The level of strains at the time of fracture of rock with a larger burden was smaller. This may be partly explained by the effect of size on the strength of rocks and partly by the increased stiffness due to an increased restraint below the bottom of the hole.
6. The orientation of the crack in Experiment no. 1 was generally along the line of least resistance; whereas, the orientation of the crack for Experiment no. 2, somewhat deviated to be parallel to the first crack. This may be due to a slight anisotropy of the rock material.
7. Only one crack appeared in each case. This explains why the expansive cement method of rock breakage is so much better than the much faster blasting technique in controlled fracture, making it so favoured for the dimension stone quarries.

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سلوك التشوه لصخر حول ثقب حفر مملوء بأسمنت قابل للتمدد

محمد حنيف

قسم هندسة التعدين ، كلية الهندسة ، جامعة الملك عبدالعزيز ، جدة
المملكة العربية السعودية

المستخلص . إن استخدام الأسمنت المتوافر والقابل للتمدد كعامل لهدم وتكسير الصخور في المناطق الأهلة بالسكان ، وكذلك أماكن وجود أحجار البناء هو في زيادة مستمرة . وهذا الأسمنت يستخدم بكثرة في المملكة العربية السعودية لتكسير الصخور في المناطق الآهلة بالسكان وفي محاجر الجرانيت والرخام .

إن المقال الحالي هو محاولة لدراسة سلوك التشوه وانشقاق الصخور الصلبة ، مثل الجرانيت ، عندما تتعرض لضغط متزايد داخل ثقب حفر مملوء بالأسمنت القابل للتمدد ، وذلك عن طريق قياس الانفعالات عند نقاط مماسة لثقب الحفر حوله . وقد تم أيضًا دراسة تأثير الحمولة (أقصر مسافة إلى الثقب من أقرب حافة) وقطر الثقب في هذا البحث .