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Development of Strain Rosette Block for Stress Measurements

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ABSTRACT

A device named strain rosette block (SRB) was developed for stress measurement in concrete tunnel lining, dam wall and pillar. The strain rosette block consists of a resin block (of near elastic compound) with standard strain rosette (45^o, 3- element rosette) mounted on one side of the block and a male 'D' connector on the other side. The SRB was connected with strain indicator and recorder through an interface cable having female 'D' connector.

The SRB was mounted on the concrete cubical block of 30 cm which was casted in the laboratory for testing purposes. Laboratory tests were conducted on the concrete cubical blocks for the development and testing of SRB. A test rig was fabricated in the laboratory to confine the cubical concrete sample along its side and to apply the desired stress level. A portable core drill was used to overcore the concrete block containing the Strain Rosette Block. A portable strain indicator with recorder was used for recording the strain. The readings were taken before and after coring of the blocks. On the bases of the results obtained during tests, calculations for the back stresses were done.

This paper describes development of the SRB and the experimental setup for testing and evaluation. The experimental setup consists of a loading frame, a portable rock drilling machine, strain indicator and recorder.

Keywords: Strain rosette block; Stress measurement; Modulus of elasticity

1. INTRODUCTION

There exist a number of methods for in-situ stress determination based on the interpretation of geological and/or stress related phenomena where no actual measurement of the stress field is performed. For measuring in-situ stresses many methods are available. Each method has distinct advantages and disadvantages. Normally, these methods are less accurate, as compared to the true measurement methods, but the information may be obtained at a lesser price and they may also serve as a complement to the true measurement methods. For certain conditions, these methods may also be useful to obtain stress field information. Typical methods that fall into this category are core-disking, borehole breakouts, and analysis of geological structures (Amadei and Stephansson, 1997; Christiansson and Hudson, 2003; Haimson, 1997; Kumar et al., 2004; Leeman, 1971; Ljunggren, 1990; Ljunggren et al., 2003; Oberg et al., 2003; Sakurai and Shimizu, 1986; Sakurai and Akutagawa, 1994; Sugawara and Obara, 1999).

Considering all the spheres of the conditions, a method similar to doorstopper (over coring) has been developed and described in the present paper. This method can be effectively used for the determination of in situ stress in concrete lining in tunnels and dam walls.

2. THE STRAIN ROSETTE BLOCK (SRB)

A cylindrical block of rubber like material of 36mm diameter and 16 mm thickness was prepared. A strain rosette was mounted on one surface of the block (Figs. 1 & 2). The rosette consists of 3- strain gauges of 10 mm length at 0^o, 45^o and 90^o angles. The gauge factor, and gauge resistance of rosette was 2.1 and 120 Ω respectively. A nine pin 'D' male connector was also mounted on the block on another side of the block. The lead wires of the strain gauges, moulded inside the block, were connected to the 'D' male connector on the other surface of the block (Fig. 2). The 'D' connector pin assignment of the Strain Rosette Block is given in Table 1.

Table 1- Assignments of pins of 'D' connector to strain gauges in Strain Rosette Block (SRB)

Pin No.	Strain Gauge No.
1	1
4	2
8	3
7	Common

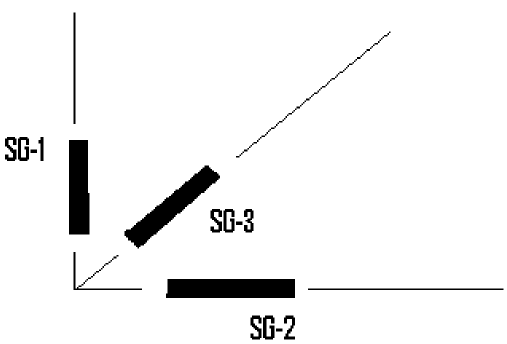


Fig. 1- Stain rosette configuration

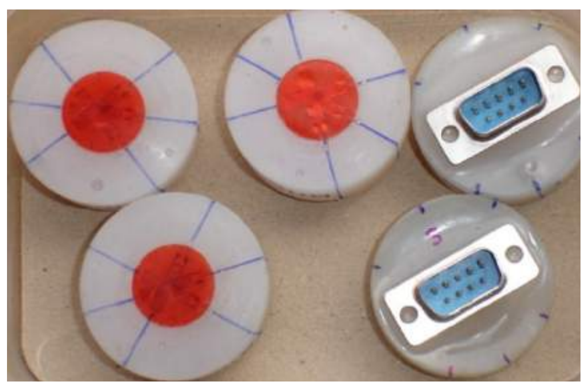


Fig. 2 - Strain rosette on the left side and the 9-pin 'D' connector mounted on the reverse side of the SRB

The individual strain gauges were connected to a 4-channel portable strain indicator/recorder in Quarter Bridge configuration with a matching female 'D' connector. The strain gauge Nos.1, 2 and 3 were connected to channels 1, 2 and 3 of the strain indicator respectively as shown in Fig. 1. A pressure transducer was also connected to the 4^{th} channel of the strain indicator.

Figure 3 shows a SRB connected to the portable strain indicator and recorder through interface cable and female 'D' connector. The light colour interface cable connects a pressure transducer to 4^{th} channel to the indicator.

Fig. 3 - Portable strain recorder with 9-pin 'D' connector connected to the SRB

3. EXPERIMENTAL SETUP

The experimental setup consists of following items:

(a) A load frame (Fig. 4) for applying bi-axial load on 0.30m cubical concrete block has been developed in the laboratory. The frame consists of iron mould to enclose the concrete blocks with facilities to apply required variable load on the side walls of cubical concrete blocks.

Arrangements for applying load on the walls of concrete block consist of the following items:

- Low profile hydraulic jack
- Spherical seating to apply uniform loading throughout the concrete block along its side-walls
- Load retaining valve which can lock the applied load on the concrete blocks for 24 hour
- Pressure gauge for measuring the applied pressure on the loading platen of the loading frame
- Various adaptors and high pressure hose (Fig. 5)
- Hand operated pump

(b) A portable rock core drilling machine (Fig. 6) has been used to make a 15 mm deep and 76 mm diameter collar hole in centre at the top of the block using a non-coring flat end bit. The Strain Rosette Block (SRB) (described in Section 1) was mounted in the center at bottom of the collar hole. The rock core drilling machine along with NX core barrel was used for coring of the gauge from the block.

(c) A four channel strain indicator and recorder model P3 Vishay Micro measurement, USA make (Fig. 3) was used for continuously recording of the strain readings from the strain gauges in the rosette.

(d) The core recovered from the concrete block has been mounted with strain rosette (Fig. 7) and a bi-axial chamber (Fig. 7) was used to measure Young's modulus of elasticity. A hand pump was used to apply required pressure to the core in the bi-axial chamber. The applied pressure and the corresponding change in strain were continuously recorded by the strain indicator and recorder.

4. EXPERIMENTAL PROCEDURE

Laboratory tests have been conducted on the concrete cubical blocks of 30 cm for the development and testing of strain gauge device. A test rig was developed and fabricated in the laboratory to confine the cubical concrete sample along its side and to apply the desired pressure (Fig. 4 & Fig. 6). The experimental procedure for stress measurement in concrete block using the SRB is as following:

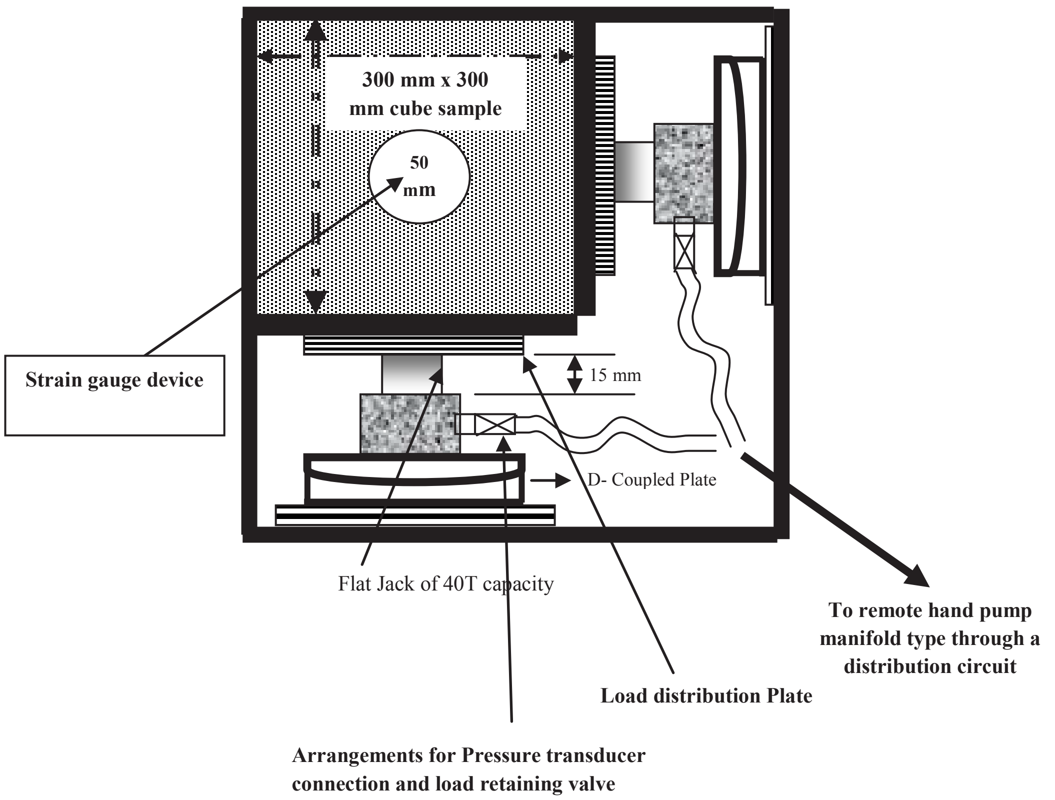
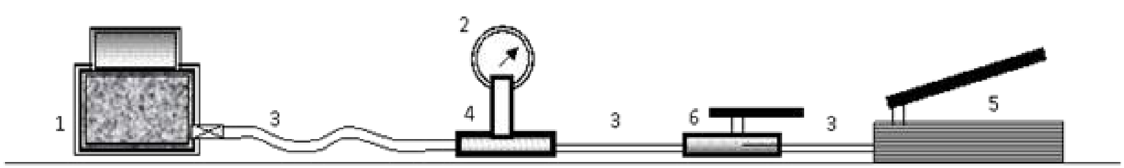


Fig. 4 - Loading frame assembly



1.Low height high capacity hydraulic cylinder; 2.Pressure gauge; 3.High pressure hose; 4. Pressure gauge adaptor (T – fitting); 5.Hydraulic pump (Two speed, light weight, minimum handle effort); 6.Manually operated load retaining valve

Fig. 5 - A setup for applying high pressure to a concrete block in the loading frame

(i) The cubical concrete test blocks of size 30cm were prepared in the laboratory using standard concrete mix [stone chips (-10 mm) : sand : cement : water = 1:1:1:0.5]. The concrete was poured in place in the test rig in layers and compacted with hand held needle vibrator. A pair of GI wires was also imbedded in the mould for lifting the concrete block out of the test rig and placing in position for testing. The test block was cured under moist jute bags for 28 days.

(ii) At centre of the top surface of the block, a 15 mm deep and 76 mm diameter collar hole was drilled using non-coring bit having flat end.
(iii) The collar hole was cleaned and left for drying.
(iv) After drying, centre lines were marked at bottom of the collar hole. Axes 1 and 2 correspond to direction of load application.
(v) The Strain Rosette Block was mounted orienting strain gauge No.1 either along axis-1 or along axis-2 in samples. In some of the samples, strain gauge No. 3 was oriented along axis-1 or 2.
(vi) The strain gauges rosette of the SRB was properly cleaned using cotton buds using cleansing liquid. The remaining portion of SRB surface (unoccupied by strain rosette) was made rough by rubbing with a rough surface. A two components special liquid adhesive material was prepared and poured in centre of the block. The oriented SRB was kept pressed for 10 minutes. The pressure was released and left for curving for four hours.
(vii) The test concrete block thus mounted with the SRB was placed in the test rig (load frame).
(viii) The strain indicator and recorder were connected to the rosette block with help of an interface cable along with the female 'D' connector. The strain gauge factor was set to 2.1 for each channel in the strain indicator matching with the strain rosette. The strain readings were balanced. The recorder was programmed to record the strain reading for every two seconds when kept in continuous recording mode. The recorder was kept on continuous recording mode during the experiment for continuous recording of strain.
(ix) Pre-defined loads on the block from two sides marked as axis-1 and axis-2 were applied by two low profile jacks of the test rig and the concrete block was kept loaded for 10 minutes with the help of load retaining valves before the load was released.
(x) After 10 minutes, the same load was re-applied on the block.
(xi) After holding the load for another 10 minutes, the SRB was disconnected from the strain recorder by carefully pulling out the female 'D' connector of the interface cable.
(xii) Rock core drilling machine attached with NX-size diamond core bit was positioned for coring the SRB. The SRB was cored and core was removed with SRB kept intact glued to the cylindrical core recovered from the concrete block.
(xiii) After wiping off the water from the male 'D' connector of the SRB, it was again connected with strain recorder using female 'D' connector and interface connecting cable. The strain was recorded in continuous mode in the strain indicator and recorder for one minute at a recording interval of 2 sec.
(xiv) The recovered core with SRB was later on placed in a bi-axial chamber such that the gauge remained in middle portion of the chamber.
(xv) Interface cable was disconnected and reconnected. This was done to record any error in connecting and disconnecting the strain recorder with the SRB.
(xvi) A pre-defined pressure was applied on the core in the bi-axial chamber. The pressure was kept on hold for few minutes before its release. This constitutes one cycle of loading and unloading of the core. This loading cycle was repeated once again.

5. RESULTS AND ANALYSIS

5.1 Modulus of Elasticity

Young's modulus of elasticity (E) of the core, recovered from coring experiment (Fig. 6), was measured by applying bi-axial pressure in a bi-axial chamber on the core mounted with the strain rosette (Figs. 7 & 8). It has been explained in experimental procedure, in steps 13 and 14 that the change in strain corresponding to release in stress was recorded by the strain indicator and recorder using a micro SD memory chip. The stress and corresponding strain data for each core were noted before and after release of stress from the recorded data and the calculations were made for the determination of modulus of elasticity. Table 2 shows results of modulus test of specimen No. 17 and 18. Young's modulus of elasticity, E was calculated using the plane stress condition.

Fig. 6 - Recovery of a cylindrical core using portable core drill

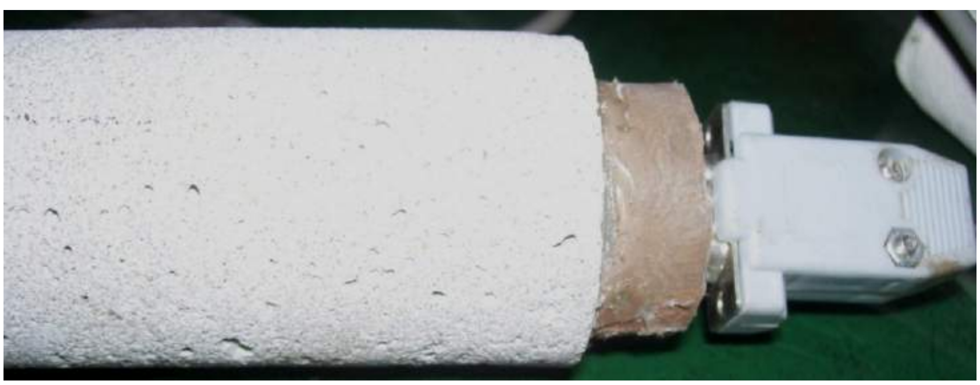


Fig. 7 - Cylindrical core mounted with SRB connected with interface cable through 9-pin 'D' connector

The results reveal that the differences in E calculated from strain readings of the three strain gauges in the rosette are not significant except for the core No.13 and 15. The Young's modulus for two cycles are almost the same. The average value of E was calculated from the two cycles and the same was used in stress computation.

5.2 Induced Strains and Stresses

The strain readings recorded during coring experiment explained in experimental procedure are given in Table 3 for experimentation on sample No. 16 in the case of SG-3 along axis-2. The connector errors were also recorded during each coring experiment as shown in Table 3. The three sets of strain readings were recorded the from the coring experiments during stress removal, coring and stress application as explained in steps 8 to 12 of experimental procedure (Section 4).

Fig. 8 - Cylindrical core containing the strain gauge device being loaded into bi-axial chamber to measure the Young's modulus of elasticity

The strain components in coordinate system 1 - 2, principal strains, principal stresses and principal directions were computed for each case using the appropriate equations.

Let e_1 = strain along strain gauge-1, SG -1
e_2 = strain along strain gauge-2, SG -2
e_3 = strain along strain gauge-3, SG -3
θ = principle strain direction from axis-1
ε_1 = principle strain along direction θ
ε_2 = principle strain along direction θ+90
σ_1 = principle stress along direction θ
σ_2 = principle stress along direction θ+90
E = Young's Modulus of elasticity
ν = Poisson's ratio
$\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{12}$ = strain components in coordinate system 1 – 2.

5.2.1 Strain components

General relation for component of strains e_θ in direction θ is given by

$$e_\theta = \varepsilon_{11} \cos^2\theta + \varepsilon_{22} \sin^2\theta + 2\varepsilon_{12} \sin\theta \cos\theta \quad (1)$$

Case -1

When strain gauge-1 is along axis-1 (Fig. 1b),

$$\varepsilon_{11} = e_1 \tag{2a}$$

$$\varepsilon_{22} = e_2 \tag{3a}$$

e_3 along – 45° from axis 1 is given by substituting θ = - 45° in Eqn. 1 as follows:

$$e_3 = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} - \varepsilon_{12} \tag{4a}$$

Solving Eqn. 4a for ε_{12}, we get

$$\varepsilon_{12} = \frac{(\varepsilon_{11} + \varepsilon_{22}) - 2e_3}{2} \tag{5a}$$

Case - 2

When strain gauge-2 is along axis –1 (Fig. 1),

$$\varepsilon_{11} = e_2 \tag{2b}$$

$$\varepsilon_{22} = e_1 \tag{3b}$$

e_3 along 45° obtained from Eqn. 1 by substituting θ = - 45° as follows:

$$e_3 = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \varepsilon_{12} \tag{4b}$$

Solving Eq. 4b for ε_{12}, we get

$$\varepsilon_{12} = \frac{2e_3 - (\varepsilon_{11} + \varepsilon_{22})}{2} \tag{5b}$$

Case - 3

When strain gauge-3 is along axis -1 (Fig. 1),

$$\varepsilon_{11} = e_3 \tag{6}$$

e_1 is obtained by substituting θ = 45° in Eq. 1 as follows:

$$e_1 = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \varepsilon_{12}$$

or $$2e_1 = \varepsilon_{11} + \varepsilon_{22} + 2\varepsilon_{12} \tag{7}$$

Similarly e_2 is obtained by substituting $\theta = -45^o$ in Eq. 1 as follows:

$$e_2 = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} - \varepsilon_{12}$$

or $$2e_2 = \varepsilon_{11} + \varepsilon_{22} - 2\varepsilon_{12} \tag{8}$$

Solving the simultaneous Eq. 7 and Eq. 8 for unknown ε_{22} and $\varepsilon_{12,}$ we get

$$\varepsilon_{22} = (e_1 + e_2) - \varepsilon_{11} \tag{9}$$

and

$$\varepsilon_{12} = \frac{e_1 - e_2}{2} \tag{10}$$

5.2.2 Principal strain direction and principal strain components

Principal strain direction θ from axis -1 is given by

$$\tan 2\theta = \frac{2\varepsilon_{12}}{\varepsilon_{11} - \varepsilon_{22}} \tag{11}$$

Substituting θ from Eq. 11 in Eq. 1, we get the principal strain component ε_1, and substituting $\theta + 90$ in Eq. 1, we get another principal strain component ε_2.

5.3 Computation of Principal Stress Components

Here, the strain gauges are mounted at the surface where there is condition of plane stress. The constitutive relation in plan stress in terms of principal stresses is given by

$$\sigma_1 = \frac{E}{1-\upsilon^2}(\varepsilon_1 + \upsilon\varepsilon_2) \tag{12}$$

and

$$\sigma_2 = \frac{E}{1-\upsilon^2}(\upsilon\varepsilon_1 + \varepsilon_2) \tag{13}$$

where E is Young's modulus of elasticity and ν is Poisson's ratio.

5.4 Computation of Elastic Modulus

The strain rosette mounted at one the end of the core was put in a bi-axial chamber and bi-axial pressure, i.e. stress $\sigma_1 = \sigma_2$ is applied in plane of the strain rosette. The stress condition is plan stress. Therefore, the constitutive relation in plans stress case relating principal strain components to principal stress components in the plane where σ_3 i.e., normal stress is zero. It is given by

$$\varepsilon_1 = \frac{1}{E}(\sigma_1 - \upsilon\sigma_2) \tag{14}$$

Solving the Eq. 12 for E and substituting $\sigma = \sigma_1 = \sigma_2$ and $e = \varepsilon_1$, we get

$$E = \frac{\sigma}{e}(1 - \upsilon) \tag{15}$$

where e = strain reading from any of the strain gauges and σ = biaxial stress.

For isotropic material, $e = e_1 = e_2 = e_3$. Thus, from the experiment we may also check the assumption of isotropy of the cored material. The Poisson's ratio has to be estimated from other sources.

5.5 Analysis of Results

During the stress measurements using the SRB, it has to be disconnected before coring from the interface cable by pulling the 9 pin 'D' connector of the cable. After the coring, the interface cable has to be connected again to the SRB by pushing the 'D' connector. The strain readings by simply connecting and disconnecting the 'D' connector should not change. The recorded connector errors are given in Table 3. The connection error lies in the range of 1 to 5 micro-strains. It is also desirable that the released strain readings are reproduced in different cycles of stress application and stress release. The modulus test on the core mounted with the SRB (Table 2) reveals that difference in strain readings in two cycles are in the range of 4 to 10 micro-strains.

Therefore, the maximum fixed error corresponds to 15 micro-strains. Its contribution to the stress value depends upon the magnitude of the released strains. Higher is the magnitude of the release strains, lower will be percentage contribution of this fixed error.

5.6 Stress Relief from Coring

The experiment was designed to verify that the strain released by coring the concrete block under known stress field is same to that of the strain released from removal of the stress field from the block. After releasing the stress field, the block was again stressed to the same level of stress before the Strain Rosette Block (SRB) was cored out from the concrete block for measuring release of strain. Theoretically, if the strain gauge device is working properly, there is negligible connection error, and the strain recovery is same in all cycles of loading and unloading, then the above three strain reading i.e. strains from stress removal, stress applied and coring should be same. For comparing the strain readings from the three cases, 1st and 2nd strain invariants were calculated. Percentage differences of the strain invariants were calculated from the case of stress application.

It was found that there is significant difference between the strain released and strain induced due to application of the same stress again. The 1st Invariant of strain (sum of normal strain component for 2D case, $I_1 = \varepsilon_{11} + \varepsilon_{22}$) release is 3% to 49% more than that of the induced strains for 13 out of 17 experiments conducted here. In most of the cases, the strain released from 1st cycle of loading is more compared to the strain induced in 2nd cycle of stress application. This is the natural phenomena observed in rock like material upon loading and unloading.

If the similar trend is followed, then the 1st Invariant of the strain released from coring of the concrete block is less than that of the previous cycle of stress application. It has been found that 1st invariant of the strain released due to coring differs by 2% to 178% from that of the induced strains. However, except four experiments out of 17, the strain release differs only by 2% to 43% from the induced strains.

6. CONCLUSIONS AND RECOMMENDATIONS

On the basis of experiments and analysis of results, following conclusions can be drawn:

(a) The developed device (SRB) in the present study can be used for measuring the in-situ stress in the concrete lining and walls of tunnel and other underground excavations using portable rock drilling machine, and strain indicator and recorder.
(b) The maximum fixed error is ±5 micro-strain in connecting and disconnecting the interface cable with the SRB using 9 pin 'D' connector. Further, the maximum fixed error in strain reproduction is ±10 micro-strain in two cycles of loading and unloading.
(c) In the laboratory experimental setup, authors are unable to correlate the strain released by coring to the strain induced or released under the same external stress. The difference is wide varying from 2% to 178%. For improving the confidence, more experiments need to be conducted and following points need to investigated:
   i. Effect of gauge temperature and temperature of water used during the coring i.e., effect of change in temperature.
   ii. The effect of water getting in contact with the SRB should be investigated. If the adhesive used has not properly sealed the gauge from water then this would lead to partial shot circuit of the lead wires of the strain gauges.

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