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TECHNICAL NOTE

Experimental Study on Stiffness Degradation of Rock Under Uniaxial Cyclic Sinusoidal Compression Loading

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1 Introduction

Improvement in the field of mining, tunneling and foundation engineering demands more effective studies on rock subjected to cyclic loading. In the past three decades, much work has been reported in the literature on the weakening of rock under cyclic loading. It may be concluded from the literature that intact rock and jointed rock masses are highly influenced by cyclic loading. Many researchers such as Burdine (1963); Attewell and Farmer (1973); Haimson (1974, 1978); Peng et al. (1974); Brighenti (1979); Singh (1989); Zhenyu and Haihong (1990); Ishizuka et al. (1990); Lajtai et al. (1991); Li et al. (1992); Ray et al. (1999); Petros et al. (2003); Bagde and Petros (2005a, b), Xiao et al. (2010); Fuenkajorn and Phueakphum (2010); Momeni et al. (2015) and Zhang et al. (2015) carried out cyclic loading experiments on different types of rock and studied the effect of stress amplitude, loading frequency and mean stress on the behavior of rock.

From the literature review, it can be concluded that different rock specimens show different responses under cyclic loading. The research reported in the literature has been oriented more towards the determination of fatigue strength of the rock, and the fatigue strength of rock depends on loading frequency, stress amplitude or mean stress. The change in rock stiffness or tangential modulus (E_{50}) with the number of cycles in uniaxial cyclic compressive loading was considered (Bagde and Petros 2005, 2009). The objective of the present study was to calculate the axial stiffness degradation for different types of rocks under uniaxial compressive sinusoidal cyclic loading with low loading frequency. For this, cyclic uniaxial compressive loading experiments are performed on intact specimens of various rocks collected from different regions in India. Kota sandstone was procured from the Kota region in Rajasthan, dolomitic limestone from a hydropower project in Himachal Pradesh and Delhi quartzite from Delhi metro project sites. The secant modulus (E) degradation is related to the number of loading cycles. From these tests, normalized relations for modulus degradation of rock are proposed.

2 Equipment and Test Scheme

2.1 Testing Equipment

The cyclic compression testing frame designed and manufactured by Heico India Private Limited with the loading capacity of 1000 kN available in the Rock Mechanics Laboratory at IIT Delhi is used for the testing. The system can be operated in stress or strain control mode and works with a servo-controlled closed-loop feedback. The testing machine conforms to the requirements as per the international standards (ASTM D3999/D3999 M-11e1 2011 and ASTM D5311/D5311 M-13 2013). The schematic diagram and a picture of cyclic loading apparatus used in this work are shown Fig. 1.

2.2 Rock Specimens

The cyclic load tests are performed on Kota sandstone, dolomitic limestone and three weathering classes of Delhi quartzite. For these rocks, the various weathering classes

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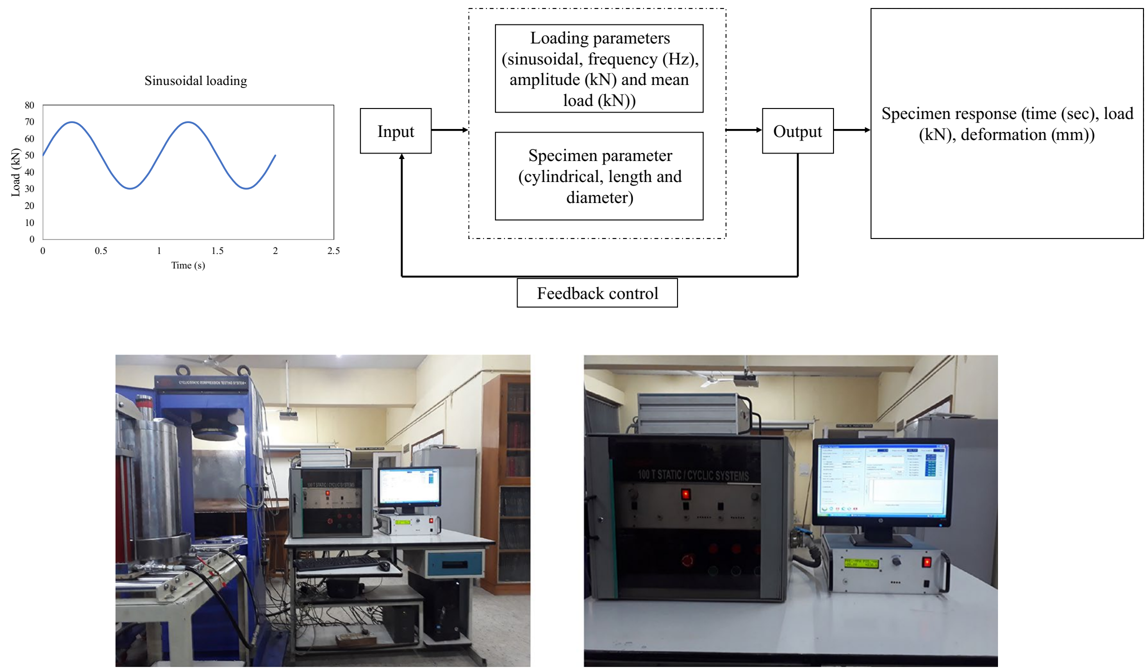


Fig. 1 Schematic and picture of cyclic compression loading frame at IIT Delhi. Input: sinusoidal compression loading output: load and deformation with time

of Delhi quartzite are further classified as per Gupta and Rao (2001). Gupta and Rao (2001) proposed a new strength ratio index (R_s) to quantify the weathering state of rock and classify the rock into five different weathering classes by determining the physical and engineering properties of Delhi quartzite, basalt and granite. In the present study, R_s is determined for three different blocks of Delhi quartzite, and these blocks are identified as slightly weathered quartzite, moderately weathered quartzite, and highly weathered quartzite.

Cylindrical rock specimens of 38 mm diameter are prepared following IS: 9179 (1979). The length to diameter ratio is 2:1 for static as well as cyclic compression testing and 0.5:1 for Brazilian tensile strength testing. Information on the block of rock with the prepared specimens is given in Table 1. To determine the dry and saturated density specimens are first saturated with water and the saturated mass is measured. After that the specimens are oven dried at 105 °C for 24 h and the dry mass is measured. In this way, all the physical properties of the specimen are obtained. The detailed procedure for determining physical properties of rocks is given in Ulusay (2015). All the Brazilian tensile strength, uniaxial and cyclic compression tests are performed on the oven dried specimens.

2.3 Testing Procedure

Various experiments are performed on the rock specimens to study the physical properties, mechanical properties, and cyclic stress–strain response. Physical properties and slake durability properties are determined as per IS: 13030 (1991) and IS: 10050 (1981), respectively. Brazilian tensile strength and uniaxial compressive strength are obtained by following the standard procedures given in IS: 10082 (1981) and IS: 9143 (1979). The Young's modulus is obtained by measuring stresses and strains as per IS: 9221 (1979). Table 2 presents the physical and mechanical properties of all rock types.

There are no guidelines in any Indian standard code to perform cyclic uniaxial experiments on rock specimens. Therefore, the standard procedure given for static uniaxial compressive strength experiments in IS: 9143 (1979)is followed in the cyclic tests. In stress control mode, the difference between static tests and cyclic tests is that there is a constant loading rate (kN/s) in static loading and in cyclic loading a sinusoidal load path having constant loading frequency, f (Hz), load amplitude, A (kN) and mean load P_m (kN) as shown in Fig. 1. The experiments are conducted with an axial load controlling system in which input parameters are the loading pattern (sinusoidal in this study), mean load, amplitude and loading frequency. Mean load is the average of the maximum and minimum of sinusoidal cyclic loads, amplitude is the difference between maximum load and mean load of sinusoidal cyclic loading and loading frequency is the inverse of time-period of sinusoidal cyclic loading.

Table 1 Rock blocks collected from site

Rock specimen	Collected from	Texture of block	Specimen
Kota sandstone	Kota, Rajasthan	Fine grained, reddish brown colour free from cracks, flaws and weathering.	
Dolomitic limestone	Koldam, Himachal Pradesh	Very fine grained, white grey colour, weathered with cracks and flaws.	
Delhi quartzite (Gupta and Rao 2001)	Jama Masjid metro station, Delhi	1. Slightly weathered: Homogenous, very fine grained, light grey colour, free from crack and flaws. 2. Moderately weathered: Non-homogenous, fine grained, reddish grey in colour, free from cracks and flaws. 3. Highly weathered: Non-homogenous, coarse grained, reddish colour, free from cracks and flaws.	  

Table 2 Physical and mechanical properties

Property	Kota sandstone	Dolomite lime-stone	Delhi quartzite		
			Slightly weath-ered	Moderately weathered	Highly weathered
Dry density (kg/m^3)	2560	2699	2530	2430	2210
Saturated density (kg/m^3)	2650	2706	2590	2532	2380
Specific gravity, G	2.71	2.87	2.64	2.65	2.67
Porosity, η (%)	9.50	0.80	0.69	10.19	16.95
Slake durability					
1st cycle (%)	99.11	99.18	99.75	93.65	68.56
2nd cycle (%)	98.20	98.96	99.10	87.72	53.11
Brazilian tensile strength, σ_t (MPa)	9.82	10.40	10.40	5.63	1.26
UCS, σ_c (MPa)	97.10	78.20	82.10	41.77	11.59
Tangential Young's Modulus, E_{50} (GPa)	9.98	10.90	48.20	13.67	1.50
Secant Modulus, E (GPa)	8.10	9.78	54.73	8.36	1.31

The axial loading path of a rock specimen is a straight line with a loading rate of 0.5 kN/s until the mean load is reached. Then it follows a sinusoidal cyclic loading path having constant amplitude and loading frequency. The specimen is loaded till failure, and stresses and strains are recorded. From the mean load (P_m) and loading amplitude (A), mean stress (σ_m) and stress amplitude (σ_a) are calculated by dividing the loads by cross-sectional area to obtain stresses. Table 3 presents the details of cyclic tests on all rock specimen. In Table 3 mean stress (σ_m), stress amplitude (σ_a) and peak stress (σ_p) are presented as an absolute value and a fraction of unconfined compressive strength (σ_c), i.e.,

Table 3 Cyclic uniaxial experiments on rock specimens

Rock specimen	UCS, σ_c (MPa)	Test number	Load application			Test results		
			Loading frequency (Hz)	Stress Amplitude, σ_a in MPa (σ_a/σ_c)	Mean stress, σ_m in MPa (σ_m/σ_c)	Peak stress/fatigue strength, σ_p in MPa (σ_p/σ_c)	Number of cycles of loading till failure (N)	Total final strain (%)
Kota sandstone	97.10	1	1	17.48 (0.18)	52.43 (0.54)	69.91 (0.72)	1189	0.890
		2	4	17.48 (0.18)	52.43 (0.54)	69.91 (0.72)	5114	0.930
		3	4	32.04 (0.33)	72.83 (0.75)	104.87 (1.08)	6	0.104
		4	4	9.71 (0.10)	67.97 (0.70)	77.68 (0.80)	2508	0.791
Dolomitic Limestone	78.20	1	1	13.30 (0.17)	17.98 (0.23)	31.28 (0.40)	6	0.301
		2	4	13.30 (0.17)	17.98 (0.23)	31.28 (0.40)	2500	0.401
Slightly weathered Delhi quartzite	82.10	1	1	13.13 (0.16)	27.92 (0.34)	41.05 (0.50)	1000	0.140
		2	1	4.10 (0.05)	12.31 (0.15)	16.42 (0.20)	1000	0.060
		3	3	12.31 (0.15)	12.31 (0.15)	24.63 (0.30)	2000	0.045
		4	3	13.13 (0.16)	60.75 (0.74)	63.88 (0.90)	12	0.080
		5	4	13.13 (0.16)	60.75 (0.74)	63.88 (0.90)	63	0.040
		6	4	12.31 (0.15)	12.31 (0.15)	24.62 (0.30)	2000	0.040
Moderately weathered Delhi quartzite	41.77	1	1	10.44 (0.25)	27.15 (0.65)	37.59 (0.90)	28	0.497
		2	3	10.44 (0.25)	27.15 (0.65)	37.59 (0.90)	25	0.402
		3	4	10.44 (0.25)	27.15 (0.65)	37.59 (0.90)	32	0.350

σ_m/σ_c, σ_a/σ_c and σ_p/σ_c, respectively. Tests are conducted with a loading frequency range of 1–4 Hz.

3 Experimental Results and Discussion

3.1 Static Experimental Results

The static stress–strain curves of various rocks are presented in Fig. 2 and the physical and static strength properties are given in Table 2. The uniaxial compressive strength (UCS) of Kota sandstone, dolomitic limestone, slightly weathered Delhi quartzite, moderately weathered Delhi quartzite and highly weathered Delhi quartzite are 97.10 MPa, 78.20 MPa, 82.10 MPa, 41.77 MPa and 11.59 MPa, respectively. The elastic tangential moduli are 9.98 GPa, 10.90 GPa, 48.20 GPa, 13.67 GPa and 1.50 GPa, all determined at 50% of the peak stress value. Thus, Kota sandstone has the greatest static compressive strength and highly weathered quartzite has the smallest static compressive strength among the five rocks. However, slightly weathered Delhi quartzite has the greatest elastic modulus among all the five rock specimens.

Strain gages, glued to the specimen using araldite glue, are used for the measurement of axial deformation. The failure in most of the specimens is observed to be brittle and hence strain gages also fail along with the specimen.

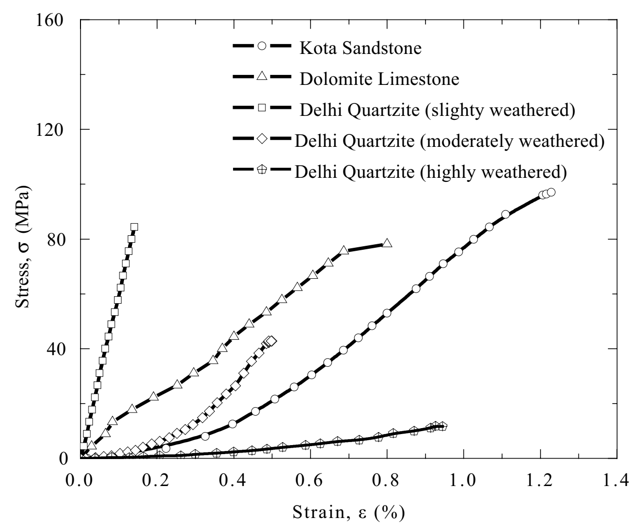


Fig. 2 Stress–strain plots of Kota sandstone, dolomitic limestone and three weathering classes of Delhi quartzite under static uniaxial compressive strength test performed at a constant loading rate of 0.5 kN/s

The stress–strain measurement is found reliable till the peak stress only. Hence, no-drop-off at failure is shown in Fig. 2.

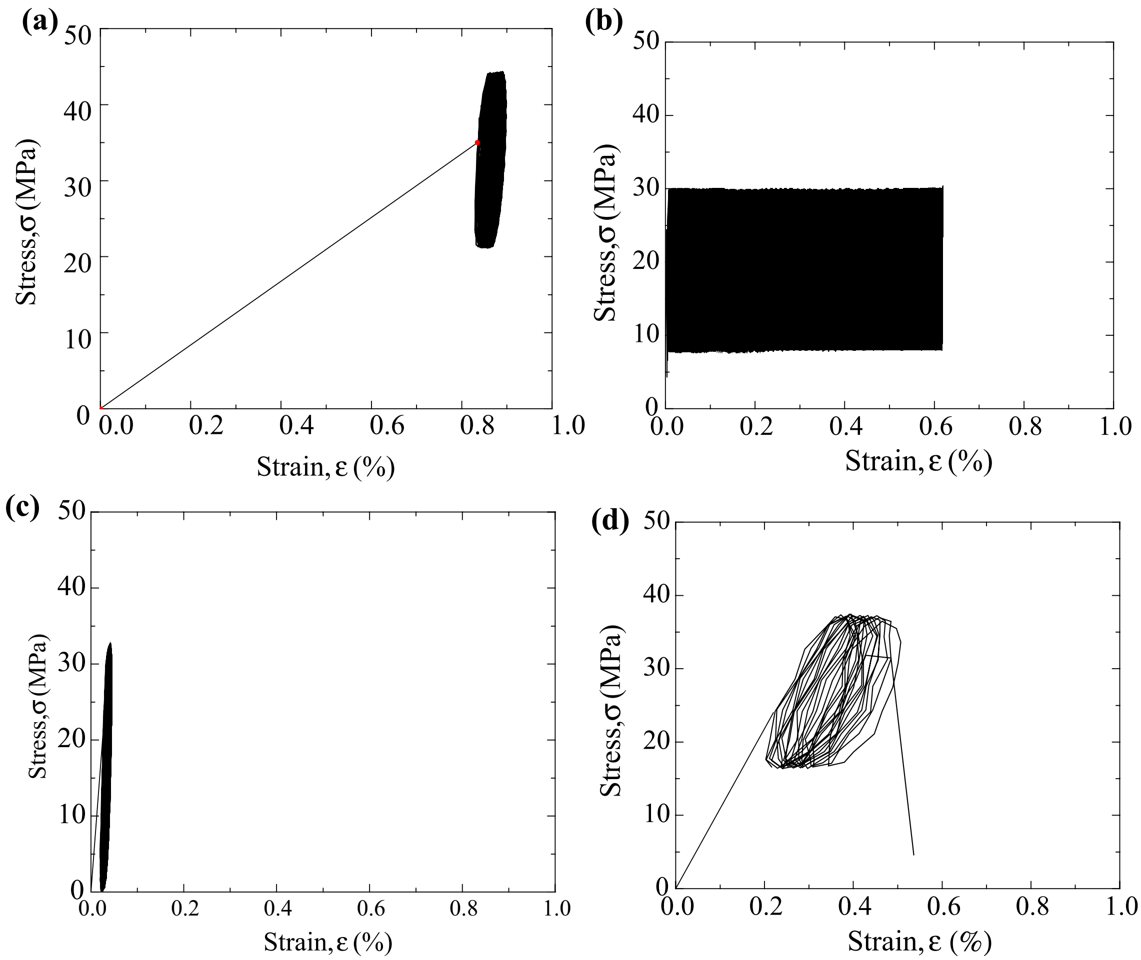


Fig. 3 Stress–strain plot of cylindrical specimen of rock under sinusoidal cyclic loading with hysteresis loops shifting on the right for **a** Kota sandstone, **b** dolomitic limestone, **c** slightly weathered Delhi quartzite and **d** moderately weathered Delhi quartzite

3.2 Stress–Strain Response in Cyclic Loading Experiments

Figure 3a–d shows typical stress–strain responses of the rocks under uniaxial compressive cyclic loading for tests at 1 Hz to 4 Hz loading frequencies. The details of the tests carried out and the summary of the results are presented in Table 3. Figure 4a–e shows the failed specimens in the tests.

The peak stress (σ_p) is the maximum stress applied on the specimen during cyclic loading and is the sum of the mean stress (σ_m) and stress amplitude (σ_a), as presented in Fig. 5. From all the experiments, cyclic fatigue strength, defined herein as peak stress value at which failure is observed in a rock specimen after *N* cycles of loading, is recorded. For each experiment, absolute values of amplitude, mean stress and peak stress of cyclic loading are shown in Table 3. The peak stress at which specimen failed can be compared with the uniaxial compressive strength (σ_c) of the specimen obtained from the static experimental results as per ASTM standard: D7012–10 2010 using a 1000-kN capacity compression testing machine in a load control mode. The loading rate for UCS test is kept 0.5 kN/s for all the experiments. From the stress–strain plots of specimens under cyclic loading shown in Fig. 3a–d, the absolute value of peak stress can be determined.

For Kota sandstone, the minimum value of peak stress at which specimen failed under cyclic loading is observed to be reduced to 69.91 MPa (Tests 1 and 2 on Kota sandstone), which is 72% of the UCS of Kota sandstone. On the other hand, in case of dolomitic limestone and slightly weathered Delhi quartzite, the failure stress is reduced to 31.28 MPa (Tests 1 and 2 on dolomitic limestone) and 24.63 MPa (Test 3 on slightly weathered Delhi quartzite), which is 40% and 30% of UCS of dolomitic limestone and Delhi quartzite rock specimens, respectively. In Test 2 on slightly weathered Delhi quartzite, the specimen is loaded till 1000 cycles of loading at peak stress of 16.42 MPa and the specimen did not fail. Therefore, it is decided that 16.42 MPa in this

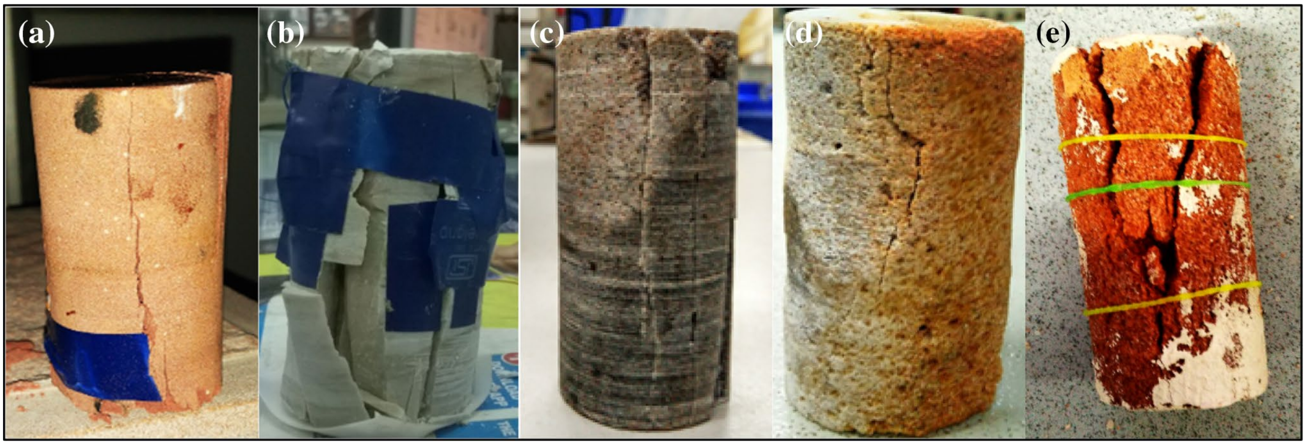


Fig. 4 Failure of the cylindrical rock specimen due to cyclic loading **a** Kota sandstone, **b** Dolomitic limestone, **c** slightly weathered Delhi quartzite, **d** moderately weathered Delhi quartzite and **e** highly weathered Delhi quartzite

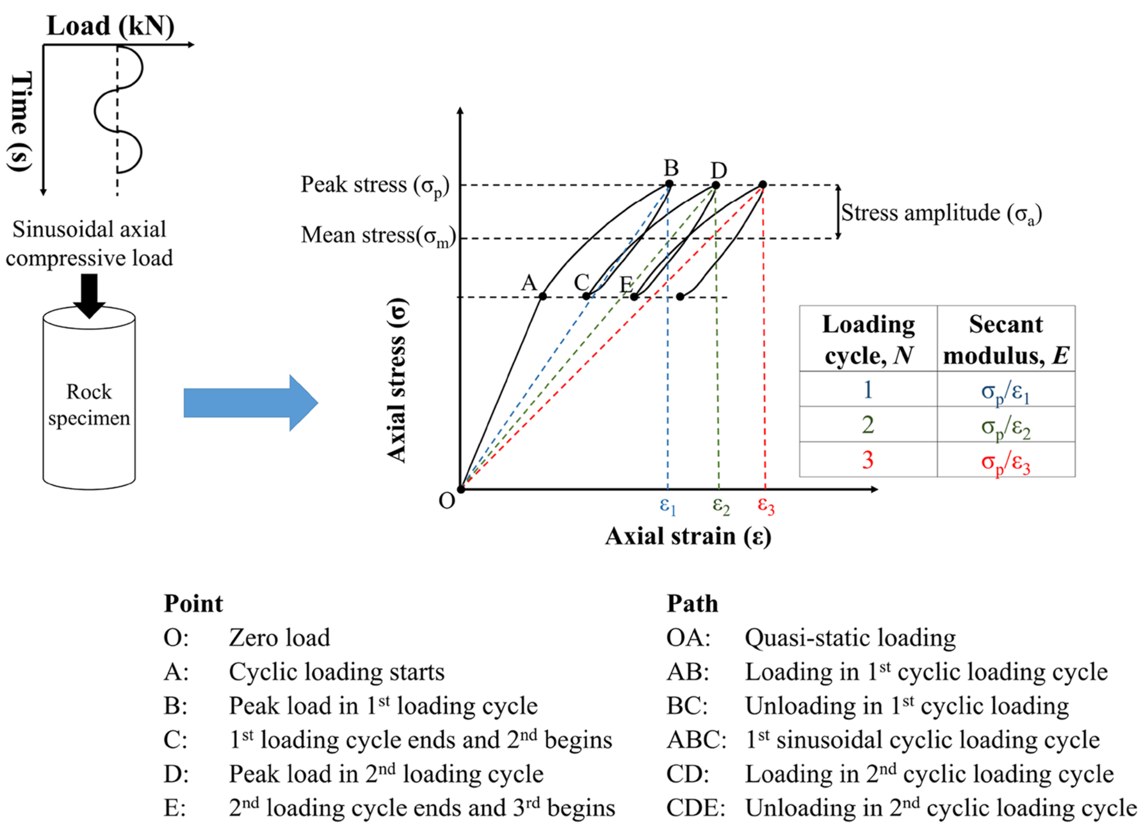


Fig. 5 Illustration of the mean stress, peak stress and calculation of the secant modulus for each loading cycle from the stress–strain data of the rock specimen under cyclic loading

test cannot be considered as the fatigue strength of rock specimen.

A series of uniaxial cyclic loading experiments are performed on the cylindrical specimen of various types of rock to study the change in fatigue strength, number of loading cycles to failure and total strain in the specimen at failure due to change in loading frequency, stress amplitude and mean stress. A complete summary of the test observations is presented in Tables 3 and 4 and discussed as follows:

The results of all the tests performed (refer to Tables 3 and 4) show that different fatigue strength (or peak stress achieved in cyclic loading) magnitudes are observed for

Table 4 Effect of cyclic loading parameters on fatigue properties of the intact rock specimen

Rock specimen	Effect of increase in loading parameter	Effect on the property		
		Peak stress/fatigue strength	Number of cycles of loading till failure	Total final strain
Kota sandstone	Loading frequency	No change	Increases	Increases
	Stress amplitude	Decreases	–	–
	Mean stress	–	–	–
Dolomitic limestone	Loading frequency	No change	Increases	Increases
	Stress amplitude	–	–	–
	Mean stress	–	–	–
Slightly weathered Delhi quartzite	Loading frequency	No change	Increases	Decreases
	Stress amplitude	–	–	–
	Mean stress	Increases	Decreases	–
Moderately weathered Delhi quartzite	Loading frequency	No change	No change	Decreases
	Stress amplitude	–	–	–
	Mean stress	–	–	–

–The effect of the change in this parameter is not studied in this research

different values of mean stress, stress amplitude and loading frequency. Hence, fatigue strength is not an inherent property, and it depends on loading parameters, i.e., stress amplitude, mean stress and loading frequency.

Overall, it can also be observed that the failure strain and peak stress in all the cyclic loading tests are lower as compared to those in static UCS tests, except in case of Test 3 on Kota sandstone (refer to Fig. 2, and Tables 2 and 3). The strain at failure in case of rock specimen when subjected to cyclic loading depends on the loading frequency and the type of rock.

Attempts are also made to conduct cyclic uniaxial compressive tests on highly weathered Delhi quartzite. As can be observed from the static stress–strain curve in Fig. 2, highly weathered Delhi quartzite has very low uniaxial compressive strength (7 MPa) and very low tangential modulus (1.5 GPa). The rock also shows minimal resistance to cyclic loading. Thus, in the very first cycle of loading the rock specimen shows substantial non-recoverable deformation.

3.3 Secant Modulus Degradation

To study the stiffness of rock specimen under static tests, the tangential Young's modulus (E_{50}) as shown in Table 2 is considered in this work. In the case of cyclic loading tests, the stress–strain loop of each loading cycle is parallel to the next loading cycle (refer to Fig. 3). Hence there is no change in tangential modulus (E_{50}) with the increase in loading cycles. However, after each loading cycle, there is some non-recoverable strain and hence the starting point of the loading cycle is offset towards the right with respect to the starting point of the previous cycle. To account for this non-recoverable deformation in the specimen, the change in secant modulus (E) with the number of loading cycles (N) is studied. The secant modulus (E) of each cycle of loading is defined as the slope of the line joining the origin and the peak stress point of that cycle of loading in a stress–strain plot. Figure 5 illustrates the calculation of secant modulus (E) after each loading cycle (N).

Figure 6a–d presents change in secant modulus (E) of Kota sandstone with number of cycles (N) for Tests 1, 2, 3 and 4 (refer to Table 3), respectively, and a trend line is set through the data points. Test 1 is conducted at a loading frequency of 1 Hz, whereas Tests 2, 3 and 4 are performed at loading frequency of 4 Hz. The number of data points taken into consideration for the E–N curve fitting is equal to the number of loading cycles (N) given in Table 3. Hence, there are 1189, 5114, 6 and 2508 data points for Tests 1, 2, 3 and 4, respectively. Figure 6e shows all trend lines together in the E vs N-space. The secant modulus E has been normalized with respect to $E_{max,}$ i.e., secant modulus of rock for the first loading cycle. It may be noted from Fig. 6e that except for Test 3 where an early failure of the specimen is observed, the secant modulus degradation of the other three tests follows a similar trend. A summary of all elastic modulus degradation equations for Kota sandstone is given in Table 5.

Figure 7a, b presents the secant modulus (E) degradation with the number of loading cycles (N) for dolomitic limestone specimen for Tests 1 and 2 (refer Table 3), respectively. Tests 1 and 2 are performed at loading frequency of 1 Hz and 4 Hz respectively and trend lines are set through the data points. Figure 7c shows all trend lines together in E vs N-space. It may be noted that in this case, Test 2 continued till a large number of cycles whereas Test 1 failed at an early stage. The number of data points for Tests 1 and 2 are 6 and 2500, respectively. In Tests 1 and 2, depending on

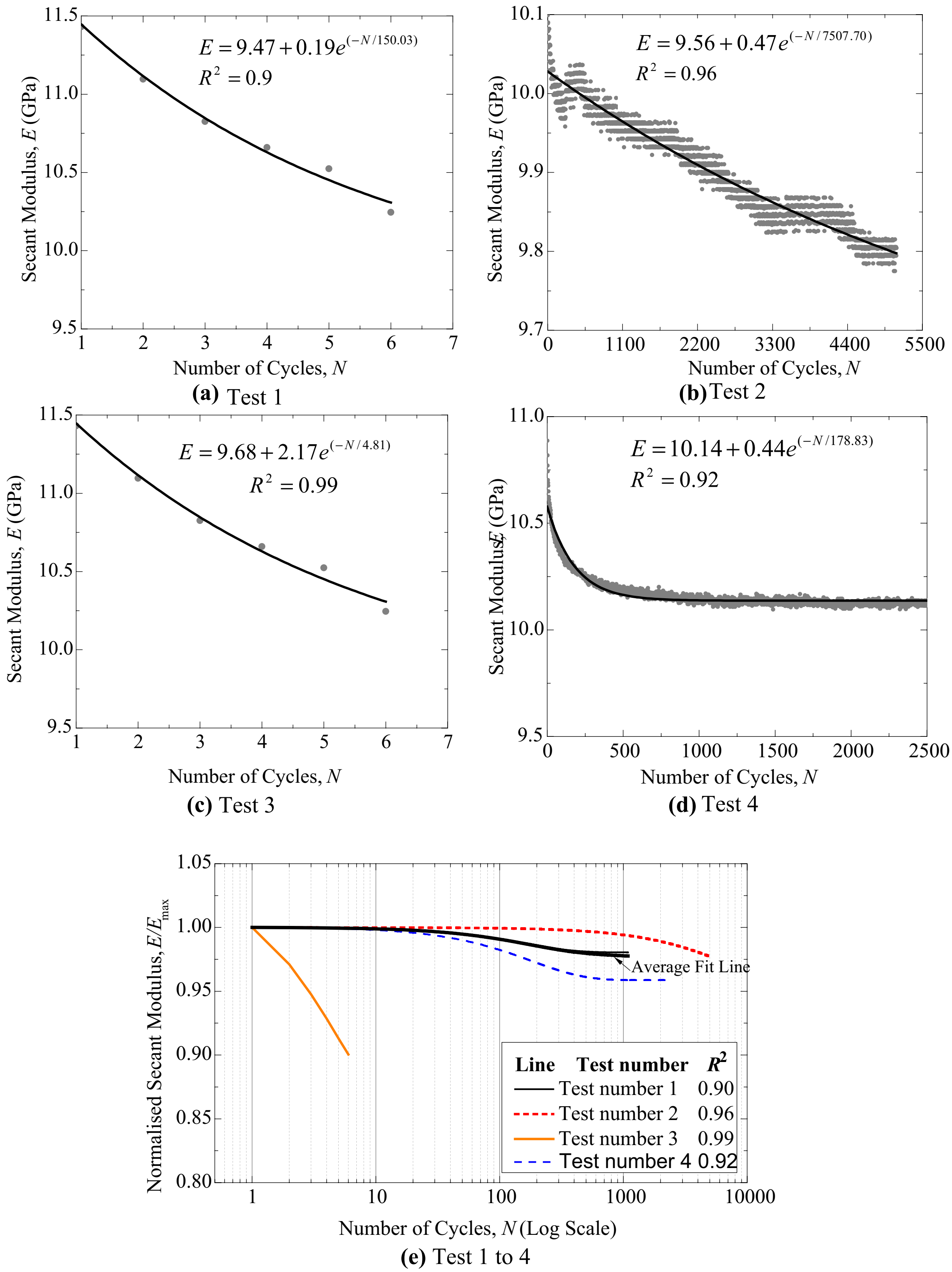


Fig. 6 Change in secant (E) of Kota sandstone with the number of loading cycles N when the specimen if under cyclic loading (Tests 1 to 4)

fracture propagation, the patterns of modulus degradation are different. A summary of all the equations for elastic modulus degradation of dolomitic limestone is given in Table 5.

Secant modulus (E) degradation data for slightly weathered Delhi quartzite with a number of cycles (N) for Tests 1, 2, 3, 4, 5 and 6 (refer to Table 3) are presented in Fig. 8a–f,

Table 5 Summary of elastic modulus degradation equations for rocks

Rock specimen	Test number	Fre-quency (Hz)	Amplitude of cyclic stress (% of UCS)	Mean stress (% of UCS)	Fitting equation (E–N relations)	R^2
Kota sandstone	1	1	18	54	$E = 9.470 + 0.191e^{(-0.007N)}$	0.90
	2	4	18	54	$E = 9.560 + 0.470e^{(-0.0001N)}$	0.96
	3	4	33	75	$E = 9.681 + 2.170e^{(-0.208N)}$	0.99
	4	4	10	70	$E = 10.140 + 0.441e^{(-0.0055N)}$	0.92
	Proposed equation				$\frac{E}{E_{max}} = 0.980 + 0.022e^{(-0.005N)}$	
Dolomitic limestone	1	1	17	23	$E = 18.730 - 7.261e^{(-0.158N)}$	0.97
	2	4	17	23	$E = 1.022 + 6.980e^{(-0.0033N)}$	0.71
	3	2	17	33	$E = 4.771 + 4.350e^{(-0.505N)}$	0.92
	Proposed equation				None	
Slightly weathered Delhi quartzite	1	1	16	34	$E = 46.810 - 0.002N$	0.87
	2	1	5	15	$E = 56.671 - 0.002N$	0.89
	3	3	15	15	$E = 56.371 - 0.004N$	0.97
	4	3	16	74	$E = 51.010 - 0.004N$	0.99
	5	4	16	74	$E = 66.830 - 0.105N$	0.79
	6	4	15	15	$E = 62.321 - 0.002N$	0.57
	Proposed equation				$\frac{E}{E_{max}} = 1 - 0.038N$	
Moderately weathered Delhi quartzite	1	1	25	65	$E = 12.170 - 0.370e^{(0.125N)}$	0.92
	2	3	25	65	$E = 12.471 - 0.340e^{(0.174N)}$	0.96
	3	4	25	65	$E = 12.501 - 0.210e^{(0.149N)}$	0.99
	Proposed equation				$\frac{E}{E_{max}} = 1.022 - 0.023e^{(0.159N)}$	

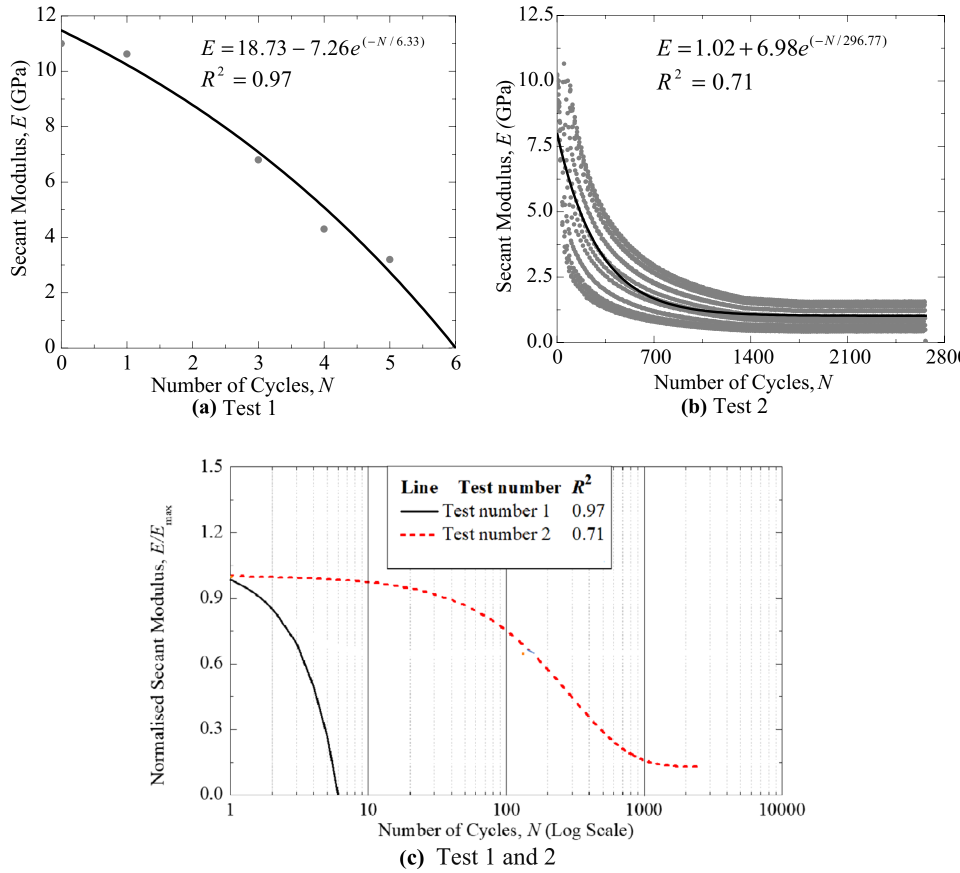


Fig. 7 Change in secant (E) of dolomitic limestone with the number of loading cycles N when the specimen if under cyclic loading (Tests 1 and 2)

respectively, and trend lines are set through the data points. The number of data points for Tests 1, 2, 3, 4, 5 and 6 are 1000, 1000, 2000, 12, 63 and 2000, respectively. Figure 8g presents all trend lines together in which the elastic modulus E has been normalized with respect to E_{max}, i.e., the secant modulus of the first loading cycle. It may be noted that except for Test 5 where early failure of the specimen was observed, the secant modulus degradation of the other three tests follows a similar trend. Table 5 presents a summary of all equations.

Secant modulus (E) degradation data for Tests 1, 2 and 3 (refer Table 3) for moderately weathered Delhi quartzite are demonstrated in Fig. 9a–c, respectively, and trend lines are set through the data points. The number of data points for Tests 1, 2 and 3 are 28, 25 and 32, respectively. Figure 9d presents all trend lines together in which the elastic modulus E has been normalized with respect to E_{max}. It is noted that all trend lines follow a similar pattern. Table 5 presents a summary of all equations.

3.4 Normalized Elastic Modulus Degradation Equations

In Table 5, secant modulus degradation equations are proposed for Kota sandstone, slightly and moderately weathered Delhi quartzite rocks by normalizing secant modulus obtained from cyclic stress–strain plots for different rock specimens with respect to the maximum secant modulus E_{max} obtained from the initial loading cycle. The equations have been proposed because the consistent trend of elastic modulus degradation is observed for these three rock types. The normalized elastic modulus degradation equation for Kota sandstone, slightly weathered Delhi quartzite and moderately weathered Delhi quartzite are given in Eqs. (1), (2) and (3), respectively, as follows:

$$\frac{E}{E_{max}} = 0.980 + 0.022e^{(-0.005N)} \tag{1}$$

$$\frac{E}{E_{max}} = 1 - 0.038N \tag{2}$$

$$\frac{E}{E_{max}} = 1.022 - 0.023e^{(0.159N)} \tag{3}$$

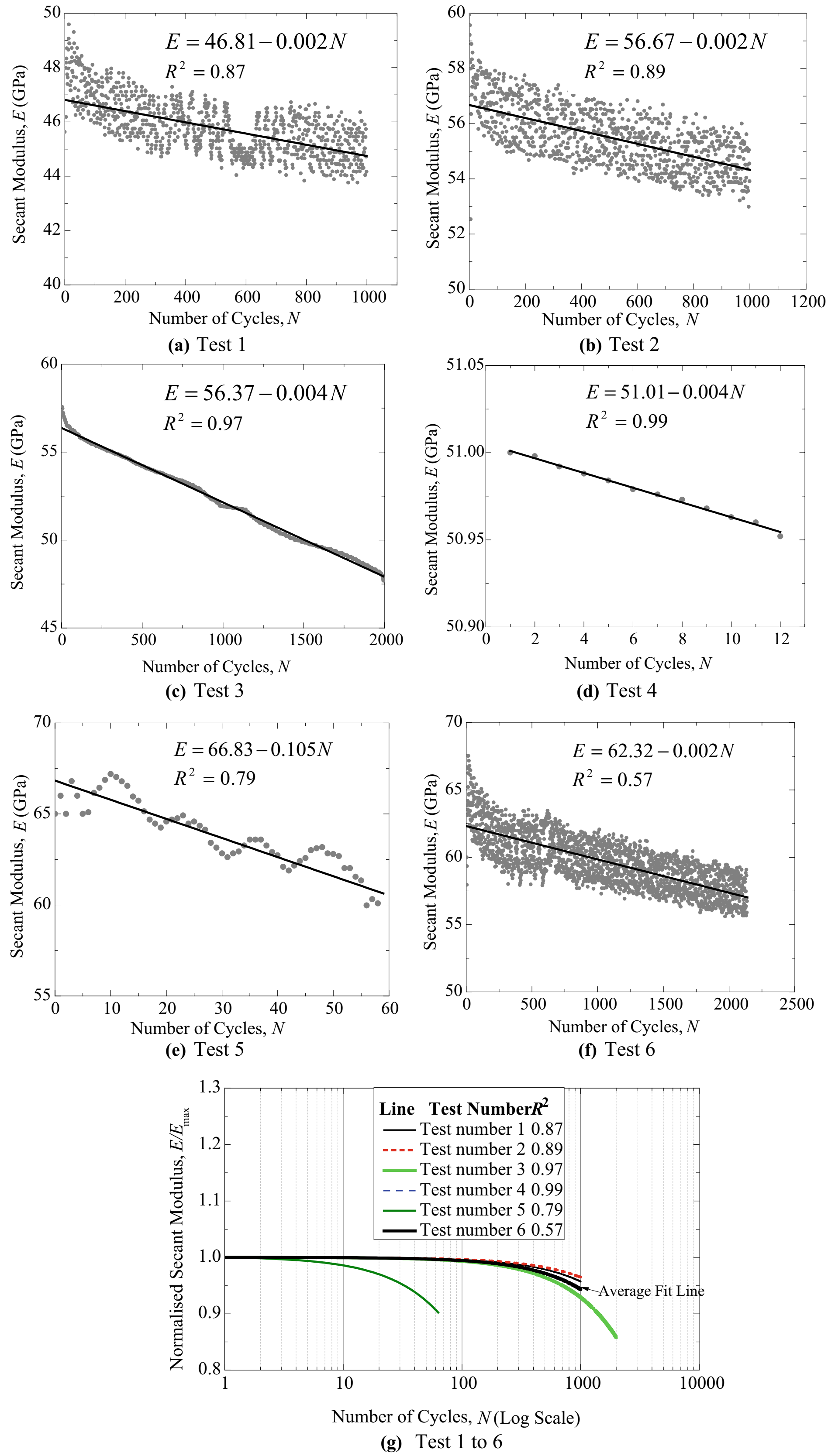
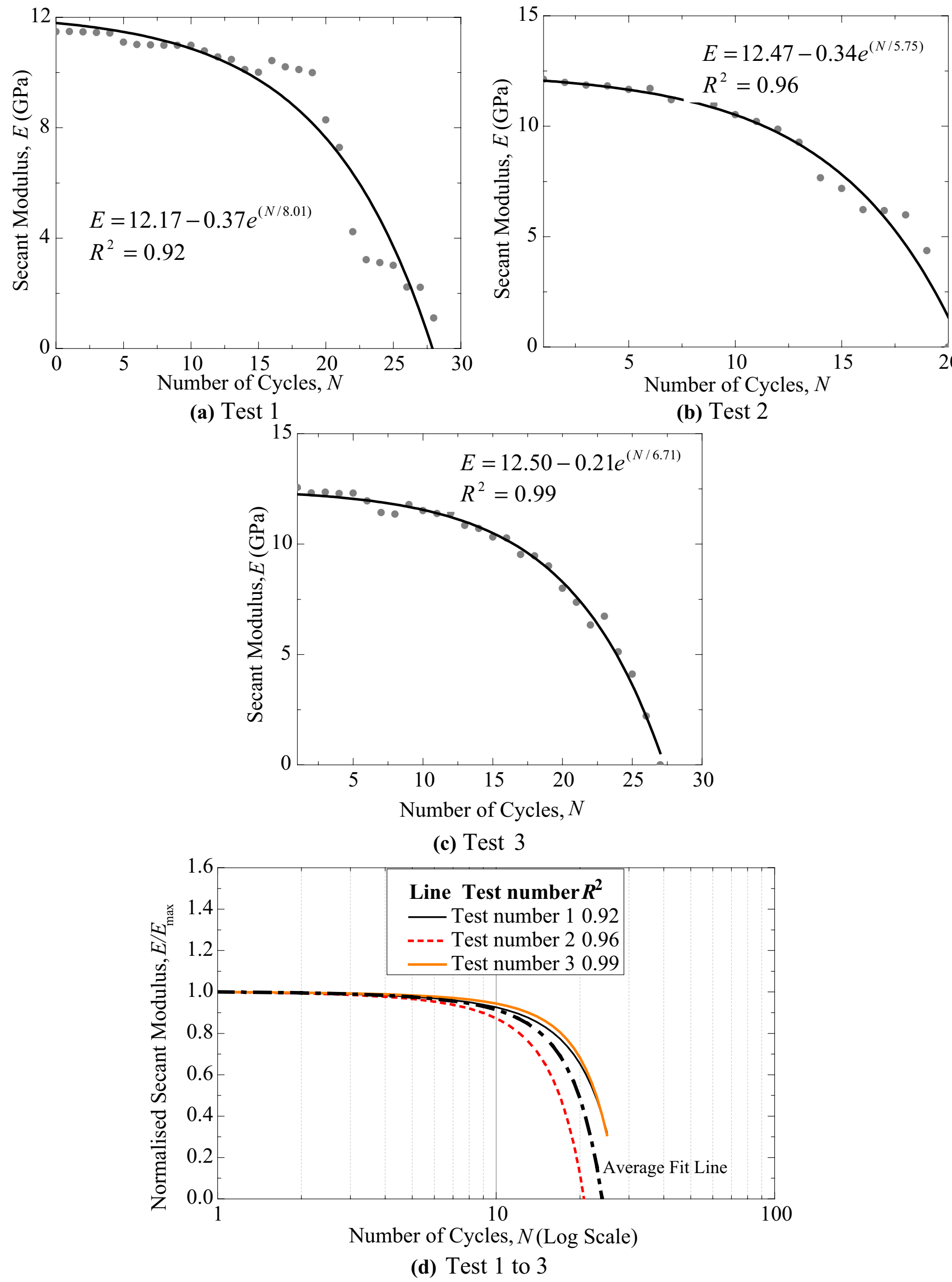


Fig. 8 Change in secant (E) of slightly weathered Delhi quartzite with the number of loading cycles N when the specimen if under cyclic loading (Tests 1 to 6)

Fig. 9 Change in secant (E) of moderately weathered Delhi quartzite with the number of loading cycles N when the specimen if under cyclic loading (Tests 1 to 3)



From these equations, it may be observed that normalized elastic modulus degradation is exponential in Kota sandstone and moderately weathered Delhi quartzite, whereas it is linear degradation in slightly weathered Delhi quartzite. Greater modulus degradation is observed for moderately weathered Delhi quartzite as compared to Kota sandstone. It may be noted that while deriving these equations, the tests which failed prematurely are ignored. No equation is proposed for dolomitic limestone because no uniform trend is observed in this rock. However, the equation proposed from Test 2 for dolomitic limestone would be applicable to intact rock specimens.

4 Conclusions

In the present work, cyclic tests on cylindrical specimens of Kota sandstone, dolomitic limestone and three weathering classes of Delhi quartzite are performed under uniaxial sinusoidal pulsating compressive cyclic loading. Fatigue characteristics of the rocks and the trend of elastic modulus degradation are investigated and the following conclusions are drawn:

1. Loading frequency affects the fatigue strength as well as the deformation of the rock specimen under cyclic

loading. For Kota sandstone, dolomitic limestone and slightly weathered Delhi quartzite, the strength is reduced to 70%, 40% and 30% of static UCS, respectively. Some evidence for the dependence of fatigue strength on the stress amplitude and mean stress of cyclic loading have been obtained but a detailed study is required to present a strong case.

2. With the increase in loading frequency, strain at failure decreases in case of slightly weathered Delhi quartzite and moderately weathered Delhi quartzite. However, Kota sandstone and dolomitic limestone behave in an opposite manner and strain at failure increases with increase in loading frequency. Hence, accumulated strain at failure is dependent on loading parameters and type of rock.
3. Secant modulus is found to be a function of a number of loading cycles with a value of R^2 greater than or around 0.90 in most of the cases. Change in secant modulus represents the degraded stiffness of the rock specimen.
4. Modulus degradation is not very significant in the case of brittle rock such as slightly weathered Delhi quartzite, and the *E*–*N* curve is linear with very mild slope, whereas in the case of less brittle rock such as Kota sandstone and moderately weathered Delhi quartzite, it follows exponential decrement path.

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