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STRENGTH AND STRAIN QUANTITIES UNDER BRITTLE COMPRESSION PROCESS OF HARD ROCKS

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ABSTRACT

Purpose. To examine the relationships between strength properties and strain quantities associated with the brittle compression process of hard brittle rocks.

Methods. The data used in this paper were obtained from laboratory uniaxial compression tests carried out on 84 different types of hard rocks in accordance with Ulusay (2015) proposed standards. The strength properties and the strain quantities were coordinated so that each of the strain quantities or their ratios is compared individually with the strength properties of the rocks as for their relationship.

Findings. In all the cases the relationships between the strain ratios and the strength parameters are stronger than when compared with individual strain quantities. A threshold level for strain ratio ε_{vf} / ε_{cd} may be assumed as the limit for fracture initiation above which the rock may experience brittle fracture failure.

Originality. Scientific sources demonstrate few laboratory studies as for strength properties-strain quantities ratio. Most of the published research has been concentrated on crack damage stress (σ_{cd}) and uniaxial compressive strength (σ_c) of characteristic stress levels during compression. The paper has performed detailed analysis of the problem using experimental results of the relationships between strength properties and strain quantities under the deformation process of hard rocks.

Practical implications. The relationships can improve our knowledge to evaluate correctly the stability of excavations, design of stable structures such as tunnels and excavations for mining and civil engineering purposes.

Keywords: *relationships, deformation process, hard brittle rocks, strength properties, stability of excavations*

1. INTRODUCTION

The strength properties of rocks are critical for designing of stable structures such as tunneling and excavations in mining and civil engineering applications. Some of the most important strength properties required for rock mechanical studies in civil and mining engineering applications include the uniaxial compression strength (*UCS*), elastic modulus (*E*), Poisson's ratio (v), compressibility or inverse of bulk modulus ($(1-2v)/E$), elastic strain energy ($½(\sigma^2/E)$), and critical strain criteria for fracture initiation ($0.3(UCS.v)/E$) etc. These strength properties are essential requirement in investigations related to rock mechanics and geotechnical studies. Similarly, the strain quantities underscore the nature of deformations process whether compression, tensional or buckling. Bieniawski (1967) showed that knowledge of the strength and deformation behaviour of rock is particularly important in determining the stability of underground excavations. The deformations/strains generated during the excavation process may lead to development of fractures in the rock mass, which may result in stability problems of the excavation. Also the displacements/strains in the excavation by reason of the applied load can lead to instability or ultimate failures/collapse of the excavation. It is important that our knowledge of the relationship between strength properties and strain quantities is increased in order to enable us evaluate correctly the stability of excavations.

Under laboratory conditions using appropriate equipment and research methodology, failure-deformation process tests can be conducted on hard brittle rocks to mimic natural conditions of rock subjected to load. The strength properties and strain quantities can be obtained through experimental determination of stress-strain characteristic behaviour curves of rocks under brittle compression. The response characteristic behaviour of rocks, deformations/strains and the strength properties up to failure strength of rock were coordinated in this paper in order to establish equations connecting them. The aim of this paper therefore is to compare the strength properties with the strain quantities that are associated with the failure-deformation process of hard brittle rocks. The data used were determined from the laboratory uniaxial compression tests carried out on 84 different types of hard rocks. The purpose was to investigate the influence of strain quantities on strength properties.

1.1. Description of strain quantities under brittle compression process of hard rocks

Figure 1 describes all the strain quantities under failure-deformation process of rock up to failure stress and indicated the strain quantities as used in this paper.

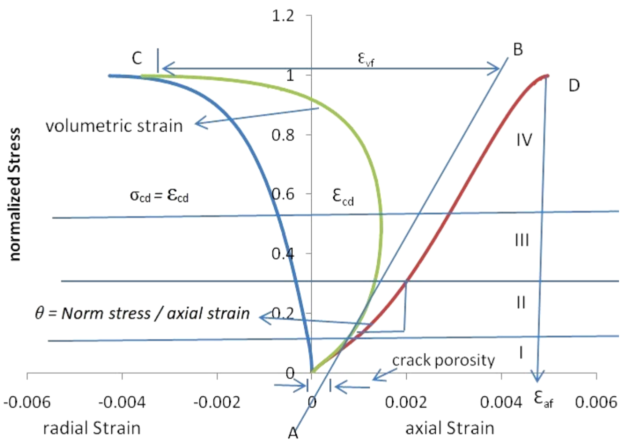

Figure 1. Normalized stress-strains curves and strain quantities

The normalized stress-strains curves were constructed by plotting the normalized stress against the three types of strains (axial, radial and volumetric) up to strength failure. The axial strain is the vertical/longitudinal deformation measurement of the test specimen under uniaxial compression test. The radial strain is the lateral/latitudinal deformation measurement of the test specimen under uniaxial compression test. The volumetric strain is estimated from axial and radial strains as $\mathcal{E}_a + 2\mathcal{E}_r$. Up to the failure strength of a rock specimen, the curves are grouped into four stages. The first stage (indicated as I in Figure 1) is termed cracks closure and is the initial compaction of rock specimen. This happen when preload is applied with the force cell drive to contact the specimen in force control mode and made the specimen and the platens (upper and lower platens) spherically seated. This stage represents the closure of pre-existing cracks. The second stage (indicated as II in Fig. 1) is termed the linear elastic deformation. At this stage there is frictional sliding on crack faces without permanent deformation. The third stage (indicated as III in Fig. 1) is termed the crack initiation and stable crack growth. This is when microcracking is initiated in the rock and mark the beginning of permanent deformation in the rock specimen. The fourth stage (indicated as IV in Fig. 1) represent unstable crack growth and this is when maximum permanent deformation is recorded in rock specimen. This starts at the point of reversal of the volumetric strain curve and is termed the crack damaged stress (σ_{cd}). It is the point at which the volumetric strain coincides with the crack-damaged stress (i.e. $\sigma_{cd} = \mathcal{E}_{cd}$, in Fig. 1). Stage IV continues up to the strength failure point when rock loses its maximum load-bearing capacity.

The strain quantities used in this paper are derived from the curves in Figure 1. A linear volumetric strain line *AB* is drawn such that the line is tangential to linear elastic deformation, stage II. The line *CB* is estimated and can be termed the "critical volumetric strain at strength failure". The critical volumetric strain at strength failure, indicated as $\mathcal{E}_{vf}$ in Figure 1 marks the total volumetric deformation of a specimen at strength failure. The maximum total volumetric strain ($\mathcal{E}_{cd}$), is the volumetric strain value that coincides with the crack-damaged stress (i.e. $\sigma_{cd} = \mathcal{E}_{cd}$ in Fig. 1). The maximum axial strain at failure, indicated as $\mathcal{E}_{af}$ in Figure 1 is the axial strain attained at the failure load or the axial strain at ultimate strength (*UCS*) of the specimen under the failure-deformation process. The author has decided to represent the slope of normalized stress-axial strain as a measure of axial strain, indicated as θ in Figure 1. This can be defined as the axial strain per unit normalised stress in the direction of application of the stress. It is calculated as the slope of linear elastic deformation of axial strain curve.

1.2. Description of strength properties under brittle compression process of hard rocks

The uniaxial compressive strength (*UCS*), the elastic modulus (*E*) and the Poisson's ratio (v) were estimated according to Ulusay (2015) suggested standards. These are the basic intact rock properties for rock characterisation. They are referred to as strength parameters in this paper. Other strength properties are derived from the combinations of two or three of the strength parameters. These other strength properties measure the elastic stability of the strength properties of the intact rock. They are referred to in this paper as "elastic stability of strength properties". These include the elastic strain energy (*U*), which is the energy spent by the compression testing system in deforming rock specimen and is estimated using Equation 1:

$$U = \frac{UCS^2}{2E}. \tag{1}$$

The magnitude of the deformation of the specimen under the compression testing system can be term the deformability or compressibility (β), and is the inverse of bulk modulus of the rock (*K*) (Equations 2 – 4):

$$\kappa = \frac{E}{3(1-2V)}; \tag{2}$$

$$\frac{1}{k} = \frac{3(1-2v)}{E}; \tag{3}$$

$$\frac{1}{k} = \beta. \tag{4}$$

It is estimated using Equation 5:

$$\beta = \frac{(1-2v)}{E}. \tag{5}$$

In addition is the critical strain criterion for fracture initiation which is an empirical criterion for fracture initiation in brittle rock under laboratory compressive failure process. The criteria state that “fracture of brittle rock will initiate when the total extension strain in the rock exceeds a critical value which is characteristic of that rock type” (Stacey, 1981). This empirical criterion is termed extension strain criterion for brittle rock (e_c). Fracture initiates when $e > e_c$ where e_c is the critical value of extension strain and e is the extension strain. Damage is induced in rock when it is stressed beyond a certain damage initiation threshold (crack initiation). The critical value of the extension strain is obtained from laboratory test by plotting axial strain against the lateral strain. The point of inflection coincides with the damage/crack initiation threshold (Fig. 2).

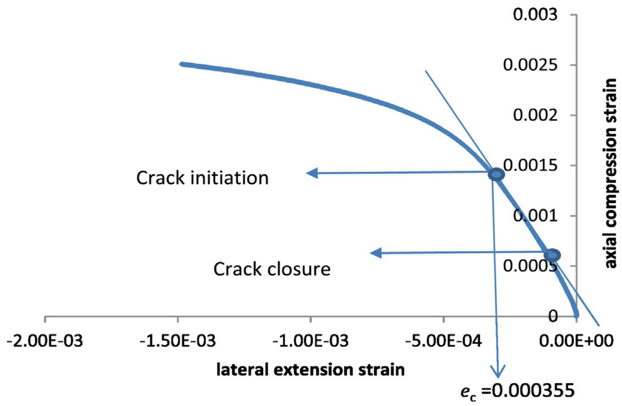

Figure 2. Extension strain criterion for brittle rock (Akinbinu, 2017)

Crack propagation of the specimen results when a critical stress value is exceeded at the crack tip. This propagation of cracks occurs at the point of reversal or inflection of the axial-lateral strains curve. It can be estimated using Equation 6:

$$e_c = \frac{0.3 \cdot UCS \cdot v}{E}. \tag{6}$$

The integer 3 in Equation 3 is a constant for all the measured values so can be ignored.

2. LITERATURE REVIEW

From literature searches to the best knowledge of the author no experimental results have been published, which described the relationship between strength properties (uniaxial compression strength (*UCS*)), elastic modulus (*E*), Poisson’s ratio (v), compressibility (β), or inverse of bulk modulus ((1-2v)/E), elastic strain energy (½(UCS^2/E)), and critical strain criteria for fracture initiation (0.3($UCS.v$)/E)) and strain quantities (critical volumetric strain at strength failure, maximum total volumetric strain, maximum axial strain and slope of linear elastic deformation of axial strain) under failure-deformation process of hard rocks. The interactions between strength properties and the deformations/strains generated as result of in-service load determined the stability of any engineering structure or excavations. It is important to increase our knowledge of the relationship between strength properties and strain quantities in order to enable us evaluate correctly the stability of excavations.

Few laboratory studies exist in the literature relating strength properties to strain quantities. Most of these published research works have been concentrated on crack damage stress (σ_{cd}) and uniaxial compressive strength (σ_c) of characteristic stress levels during compression (Cai et al., 2004; Katz & Reches, 2004; Andersson, Martin, & Stille, 2009; Palchik, 2009; Stefanov, Chertov, Aidagulov, & Myasnikov, 2011; Nicksiar & Martin, 2012; Xue et al., 2013; Xue et al., 2014). For example, Palchik (2012) evaluated the relationship between stress levels (crack damage stress (σ_{cd}) and uniaxial compressive strength (σ_c) and strain characteristics (maximum total volumetric strain ($\mathcal{E}_{cd}$)), axial failure strain ($\mathcal{E}_{af}$), porosity (n) and elastic constants (elastic modulus (E)) and Poisson’s ratio (v)) with the existence of two different types (type 1 and type 2) of volumetric strain curves and concluded that there is no connection between the types of the volumetric strain curves and the values. Pérez Hidalgo & Nordlund (2012) compared the stress levels (at crack closure, linear elastic deformation, crack initiation and unstable crack growth) with strains at each deformations stage and for each specimen of Fennoscandian rock and link it with the geology of the rock. They concluded that the normalized crack damage lateral strain and the volumetric strain quantities were strongly affected by the grain size. Kim, Lee, Cho, Choi, & Cho (2014) identified the crack initiation and damage stress thresholds of granite using *AE* activity. They concluded that the crack initiation threshold was found at a stress level of 0.42 – 0.53 σ_c, and the crack damage threshold was identified at 0.62 – 0.84 σ_c. Yang (2016) investigated the deformation, peak strength and crack damage behaviour of hollow sandstone specimens under different confining pressures and concluded that the peak strength and crack damage parameters of hollow sandstone depend the confining pressure (σ_3) and the hole diameter. Rigopoulos, Tsikouras, Pomonis, & Hatzipanagiotou (2011) concluded that initiation and propagation of microcracks under uniaxial compressive stress is depended on the mineralogical and textural characteristics and that it may assist in the prediction of potential development of failure surfaces in an ultrabasic rock.

3. METHOD

The 84 various rocks were tested under unconfined uniaxial compression using closed loop servo-controlled testing system (MTS 815 testing machine) in accordance to suggested standards by Ulusay (2015). The strength parameters were estimated according to Ulusay (2015) suggested standards. In this case the *UCS* is the stress level at specimen failure load. The elastic modulus (E), is estimated as the average modulus of the slope of linear portion of axial stress-strain curves and the Poisson’s ratio (v), is calculated from the ratio of the slope of axial stress-strain curve to the slope of diametric stress-strain curve. The elastic strain energy (U) compressibility (β) and the extension strain criterion for brittle rock (e_c) were estimated using Equations 1 – 6.

The strain quantities were estimated using the values from the strain curves as illustrated in Figure 1. This is described at paragraph three in the introduction part of this work. From Figure 1 the critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) is estimated as the magnitude of the size of the line *CB* multiplied by the scale of the strains axis. The maximum total volumetric strain ($\mathcal{E}_{cd}$), is estimated as the strain value that coincides with the crack-damaged stress, i.e. $\sigma_{cd} = \mathcal{E}_{cd}$ see Figure 1. The maximum axial strain ($\mathcal{E}_{af}$) in Figure 1 is the axial strain value attained at the failure stress of the specimen under the failure-deformation process. The slope of linear elastic deformation of axial strain curve, indicated as θ, is calculated as the value estimated from the slope of axial strain curve measured within the linear elastic deformation stage II in Figure 1.

4. RESULTS AND DISCUSSION

Table 1 shows the strength properties for the 84 different rock types with *UCS* values range from 43.67 to 640.90 MPa with an average value of 216.10 MPa and *E* values range from 25 to 150 GPa with an average value of 69 GPa; and *v* values range from 0.0824 to 0.4108 with an average value of 0.2315. The values for the elastic strain energy range from 18.3372 to 1369.1760 kJ with an average value of 302.9542 kJ. The values for the compressibility constant estimated using Equation 5 range from 0.001342 to 0.02985 GPa^{-1} with an average value of 0.008198 GPa^{-1}. The critical strain criterion for fracture initiation as calculated using Equation 6 range from 0.02076 to 0.38117 with an average value of 0.17462.

The values for the strain quantities are as follows. The critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) values range from 0.0001 to 0.0014 with an average value of 0.000593. The maximum total volumetric strain ($\mathcal{E}_{cd}$), values range from 0.00025 to 0.00324 with an average value of 0.00114. The maximum axial strain ($\mathcal{E}_{af}$) values range from 0.00026 to 0.00526 with an average value of 0.00268. The slope of linear elastic deformation of the axial strain curve (θ) values range from 46 to 84 with an average value of 69.0723.

The strength properties and the strain quantities were coordinated such that each of the strain quantities is compared individually with the strength properties of the rocks to see if there exists a relationship. The strain quantities were compared with the strength parameters (*UCS*, *E* and *v*). The strain quantities were also compared with the elastic stability of strength properties of the rocks (i.e. magnitude of deformation or deformability of the specimen, compressibility), energy spent by the compression testing system in deforming the specimen (elastic strain energy) and the critical strain criteria for fracture initiation. Similarly, the ratios of the strains quantities were compared with both the strength parameters and the elastic stability of strength properties of the rocks. These are discussed in the following paragraphs.

4.1. Strain quantities and strength parameters

The strain quantities (critical volumetric strain at strength failure, maximum total volumetric strain, maximum axial strain and slope of linear elastic deformation of the axial strain curve) were compared with the strength parameters (*UCS*, *E* and *v*) of the rocks.

4.1.1. Critical volumetric strain at strength failure and strength parameters

The critical volumetric strain at strength failure is first compared with the *UCS* of the rocks. The comparison shows a linear relationship, meaning that as the *UCS* of the rock increases so also the critical volumetric strain at strength failure (Fig. 3).

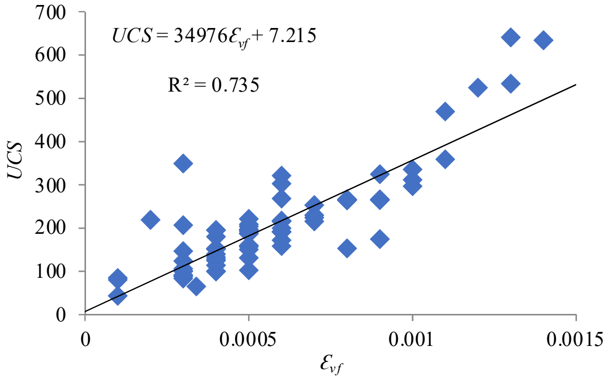

Figure 3. UCS and $\mathcal{E}_{vf}$

It can therefore be assumed that higher strength rocks will induce larger total deformation on the specimen at strength failure than lower strength rocks. Thus, the higher the strength of rock, the more deformed the specimen is at strength failure. The more deformed a specimen at strength failure the more the instability and more violent at the failure strength. Hence higher strength rock will constitute higher structural instability or elastic instability at failure and more difficult to be controlled. Consequently, the structural failure of high strength rocks will be violent or catastrophic in nature.

Similarly, the critical volumetric strain at strength failure is compared with the elastic modulus of the rocks. However, no relationship exists between them. The critical volumetric strain at strength failure is then compared with the ratio of elastic modulus of the rocks to the *UCS*, i.e. *E/UCS*. The critical volumetric strain at strength failure has logarithmic form of relation with the ratio *E* and the *UCS* (Fig. 4).

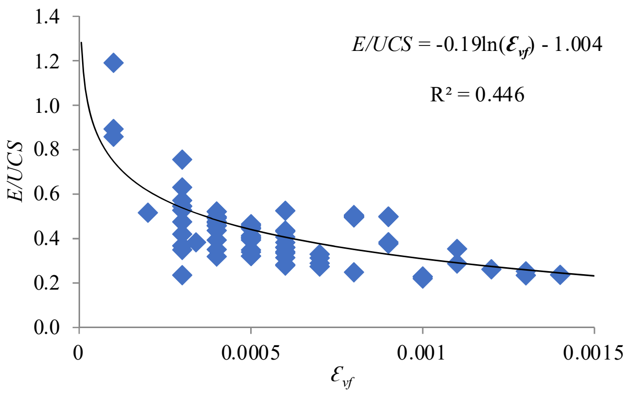

Figure 4. E/UCS and $\mathcal{E}_{vf}$

Therefore, as the ratio *E/UCS* increases the critical volumetric strain at strength failure decreases by logarithmic form of the equation.

Table 1. Strength properties and strain quantities

UCS	*E*, GPa	*ν*	*E*/*UCS*	$\sigma^2/2E$, kJ	β, GPa^{-1}	e_c	$\mathcal{E}_{vf}$	$\mathcal{E}_{af}$	$\mathcal{E}_{cd}$	θ
1	2	3	4	5	6	7	8	9	10	11
157.53	65	0.2106	0.412620	190.8900	0.008905	0.153119	0.0005	0.00254	0.00095	71.0
174.82	67	0.2255	0.383251	228.0749	0.008194	0.176516	0.0009	0.00273	0.00089	72.5
533.80	135	0.2782	0.252904	1055.3420	0.003286	0.330007	0.0013	0.00423	0.00098	82.0
524.60	137	0.2717	0.261151	1004.3980	0.003333	0.312118	0.0012	0.00411	0.00098	79.0
302.92	131	0.2451	0.432457	350.2310	0.003892	0.170028	0.0006	0.00226	0.00070	79.0
359.10	127	0.3097	0.353662	507.6882	0.002997	0.262709	0.0011	0.00300	0.00057	81.0
206.97	113	0.1436	0.545973	189.5424	0.006308	0.078905	0.0003	0.00201	0.00090	71.5
640.90	150	0.2929	0.234046	1369.1760	0.002761	0.375439	0.0013	0.00452	0.00097	81.0
634.23	150	0.3005	0.236507	1340.8260	0.002660	0.381172	0.0014	0.00445	0.00089	82.5
321.22	140	0.1768	0.435838	368.5082	0.004617	0.121696	0.0006	0.00244	0.00075	76.0
469.68	135	0.2949	0.287430	817.0345	0.003039	0.307797	0.0011	0.00375	0.00077	80.5
215.67	71	0.2088	0.329207	327.5602	0.008203	0.190276	0.0007	0.00326	0.00110	73.0
208.85	67	0.1845	0.320804	325.5099	0.009418	0.172535	0.0005	0.00351	0.00133	68.5
160.01	71	0.2209	0.443722	180.3042	0.007862	0.149350	0.0005	0.00231	0.00091	63.0
203.97	71	0.1801	0.348090	292.9842	0.009011	0.155218	0.0005	0.00304	0.00119	70.0
195.13	78	0.1945	0.399734	244.0751	0.007833	0.145972	0.0005	0.00026	0.00131	61.0
195.82	77	0.1816	0.393218	248.9966	0.008270	0.138549	0.0004	0.00262	0.00128	59.0
197.43	80	0.2171	0.405207	243.6163	0.007073	0.160733	0.0005	0.00259	0.00111	63.0
133.14	66	0.1941	0.495719	134.2898	0.009270	0.117466	0.0004	0.00212	0.00093	63.0
151.53	66	0.1887	0.435557	173.9496	0.009433	0.129971	0.0004	0.00243	0.00100	67.0
124.72	65	0.1936	0.521167	119.6544	0.009428	0.111442	0.0004	0.00200	0.00086	66.0
140.02	73	0.2219	0.521354	134.2849	0.007619	0.127687	0.0004	0.00205	0.00097	63.5
146.95	80	0.2147	0.544403	134.9644	0.007133	0.118313	0.0003	0.00205	0.00092	65.5
106.38	67	0.1753	0.629818	84.45302	0.009693	0.083500	0.0003	0.00183	0.00077	64.5
124.28	71	0.1822	0.571291	108.7713	0.008952	0.095678	0.0003	0.00181	0.00091	62.0
180.30	85	0.1651	0.471436	191.2241	0.007880	0.105062	0.0004	0.00255	0.00086	79.0
324.49	122	0.2322	0.375975	431.5318	0.004390	0.185278	0.0009	0.00276	0.00096	73.0
215.37	113	0.2833	0.524678	205.2400	0.003835	0.161985	0.0006	0.00202	0.00048	78.5
221.35	75	0.1958	0.338830	326.6388	0.008112	0.173361	0.0005	0.00311	0.00118	68.0
224.30	70	0.2025	0.312082	359.3606	0.008500	0.194660	0.0007	0.00340	0.00130	68.5
335.70	77	0.2156	0.229371	731.7824	0.007387	0.281988	0.0010	0.00452	0.00166	63.0
199.89	72	0.2198	0.360198	277.4723	0.007783	0.183066	0.0006	0.00295	0.00114	69.0
128.14	61	0.1751	0.476042	134.5890	0.010652	0.110347	0.0004	0.00232	0.00094	71.0
158.40	53	0.1526	0.334596	236.7034	0.013109	0.136822	0.0006	0.00356	0.00152	74.0
193.06	62	0.1440	0.321144	300.5820	0.011484	0.134519	0.0005	0.00377	0.00168	73.0
253.06	73	0.1954	0.288469	438.6258	0.008345	0.203211	0.0007	0.00373	0.00149	66.0
311.65	71	0.2234	0.227820	683.9840	0.007792	0.294180	0.0010	0.00470	0.00165	73.0
296.69	65	0.1794	0.219084	677.1150	0.009865	0.245659	0.0010	0.00526	0.00203	72.0
101.13	48	0.1789	0.474637	106.5341	0.013379	0.113076	0.0003	0.00219	0.00092	74.0
89.88	33	0.1291	0.367156	122.4002	0.022479	0.105486	0.0003	0.00332	0.00169	62.0
91.72	32	0.1214	0.348888	131.4462	0.023663	0.104389	0.0003	0.00336	0.00182	62.0
83.46	35	0.1449	0.419363	99.50817	0.020291	0.103657	0.0003	0.00252	0.00152	65.5
114.24	40	0.1746	0.350140	163.1347	0.016270	0.149597	0.0004	0.00312	0.00144	64.0
100.40	32	0.1058	0.318725	157.5025	0.024638	0.099584	0.0004	0.00409	0.00231	64.0
188.31	74	0.2131	0.392969	239.5990	0.007754	0.162685	0.0005	0.00257	0.00122	63.0
217.34	74	0.2179	0.340480	319.1667	0.007624	0.191993	0.0006	0.00297	0.00134	69.0
186.98	76	0.2155	0.406461	230.0100	0.007487	0.159056	0.0005	0.00250	0.00118	64.0
194.99	97	0.2268	0.497461	195.9851	0.005633	0.136774	0.0004	0.00206	0.00093	66.0
150.59	70	0.2251	0.464838	161.9811	0.007854	0.145276	0.0005	0.00220	0.00100	64.0
191.17	73	0.2363	0.381859	250.3149	0.007225	0.185644	0.0006	0.00265	0.00125	60.5
153.21	70	0.2060	0.456889	167.6665	0.008400	0.135263	0.0004	0.00229	0.00119	61.0
131.55	59	0.2513	0.448499	146.6560	0.008431	0.168094	0.0005	0.00219	0.00092	66.0
99.87	49	0.2305	0.490638	101.7757	0.011000	0.140939	0.0004	0.00209	0.00089	66.0
83.05	49	0.2470	0.590006	70.38064	0.010327	0.125592	0.0003	0.00160	0.00748	61.0
87.40	66	0.2545	0.755149	57.86939	0.007439	0.101106	0.0003	0.00130	0.00065	59.5
102.69	47	0.2516	0.457688	112.1834	0.010570	0.164916	0.0005	0.00215	0.00084	65.0
191.50	54	0.1771	0.281984	339.5579	0.011959	0.188415	0.0006	0.00366	0.00216	53.5
230.04	63	0.2069	0.273865	419.9873	0.009305	0.226644	0.0007	0.00371	0.00188	61.0
218.99	113	0.1513	0.516005	212.1974	0.006172	0.087964	0.0002	0.00197	0.00127	54.0
349.50	82	0.0982	0.234621	744.8186	0.009800	0.125564	0.0003	0.00428	0.00324	46.0

Continuation of Table 1

1	2	3	4	5	6	7	8	9	10	11
172.05	54	0.2230	0.313862	274.0852	0.010259	0.213151	0.0006	0.00316	0.00159	60.0
100.55	53	0.1994	0.527101	95.38021	0.011343	0.113489	0.0003	0.00199	0.00109	62.0
192.11	69	0.2324	0.359169	267.4366	0.007757	0.194115	0.0006	0.00279	0.00127	61.0
153.35	38	0.1940	0.247799	309.4240	0.016105	0.234868	0.0008	0.00400	0.00204	61.0
215.67	60	0.1666	0.278203	387.6129	0.011113	0.179653	0.0006	0.00376	0.00214	58.5
268.48	109	0.2389	0.405989	330.6491	0.004791	0.176532	0.0006	0.00253	0.00102	64.0
152.34	70	0.1620	0.459498	165.7677	0.009657	0.105767	0.0004	0.00240	0.00143	62.0
85.09	73	0.1565	0.857915	49.59115	0.009411	0.054726	0.0001	0.00118	0.00075	58.5
80.63	72	0.1496	0.892968	45.14720	0.009733	0.050259	0.0001	0.00112	0.00072	59.5
43.67	52	0.0824	1.190749	18.33720	0.016062	0.020760	0.0001	0.00086	0.00067	47.5
65.27	25	0.1268	0.383024	85.20346	0.029856	0.099315	0.00034	0.00294	0.00176	60.5
264.72	133	0.3939	0.502418	263.4462	0.001595	0.235203	0.0008	0.00198	0.00029	84.0
265.14	133	0.4107	0.501622	264.2828	0.001343	0.245623	0.0008	0.00200	0.00025	83.0
266.52	133	0.3954	0.499024	267.0410	0.001573	0.237704	0.0009	0.00200	0.00028	83.5
266.52	132	0.4021	0.495272	269.0641	0.001483	0.243563	0.0008	0.00201	0.00029	83.0
266.52	132	0.3978	0.495272	269.0641	0.001548	0.240958	0.0008	0.00201	0.00029	82.0
265.13	132	0.4108	0.497869	266.2648	0.001352	0.247535	0.0009	0.00200	0.00026	82.0
265.13	132	0.3941	0.497869	266.2648	0.001605	0.237472	0.0008	0.00201	0.00030	82.0
265.13	132	0.4044	0.497869	266.2648	0.001448	0.243679	0.0009	0.00201	0.00027	83.5
265.14	132	0.4018	0.497850	266.2849	0.001488	0.242121	0.0008	0.00201	0.00027	81.5
265.15	132	0.4093	0.497831	266.3050	0.001374	0.246650	0.0008	0.00201	0.00026	82.5
264.81	134	0.3902	0.506023	261.6580	0.001639	0.231333	0.0008	0.00198	0.00029	83.0
265.15	132	0.3848	0.497831	266.3050	0.001745	0.231886	0.0008	0.00201	0.00032	81.5

It can therefore be assumed that rocks with lower ratio of *E/UCS* will induce larger total deformation on the specimen at strength failure than rocks with higher ratio *E/UCS*. Thus, the lower the ratio of *E/UCS* of rock, the more deformed the specimen at strength failure. Therefore, rocks with lower *E/UCS* ratio will constitute higher structural instability or elastic instability at strength failure. Hence the structural instability of rock depends also on *E/UCS* ratio.

The comparison of the critical volumetric strain at strength failure with Poisson's ratio shows power form relationship (Fig. 5).

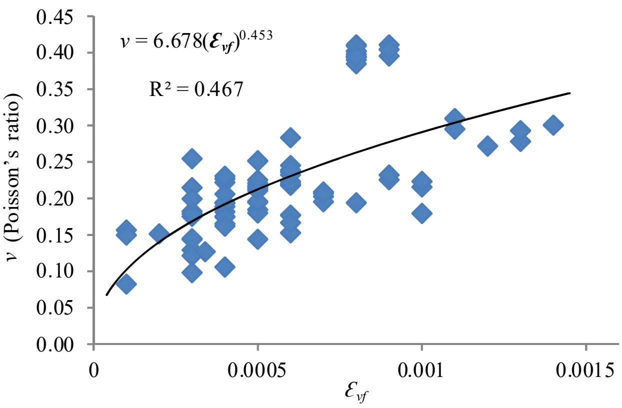

Figure 5. Poisson's ratio (v) and $\mathcal{E}_{vf}$

The higher the critical volumetric strain at strength failure, the higher is the value of Poisson's ratio. The relationship between Poisson's ratio and critical volumetric strain at strength failure may be viewed from the magnitude of the inherent crack porosity of the rock at stage I (Fig. 1). At this stage, the stress-strain curve is slightly inclined towards the axial strain. The stress-strain curve is nonlinear and expresses an increase in axial stiffness (i.e. deformation modulus). The size of this nonlinearity depends on the initial crack density and geometrical characteristics of the crack population (Eberhardt, Stead, & Stimpson, 1999). Rocks with higher inherent crack porosity may show higher value for Poisson's ratio. Porous rocks or less compacted rocks samples may exhibit higher Poisson's ratio. The deformation at the crack closure stage becomes larger and thereby contributes to the increase in the value of critical volumetric strain at strength failure.

4.1.2. Maximum total volumetric strain and strength parameters

The maximum total volumetric strain ($\mathcal{E}_{cd}$) is compared with the strength parameters of the rocks. The comparisons show that only elastic modulus and Poison's ratio are related to maximum total volumetric strain ($\mathcal{E}_{cd}$) (Fig. 6, 7).

The elastic modulus has correlation coefficient of 0.51 while Poison's ratio shows stronger coefficient of correlation of 0.73.

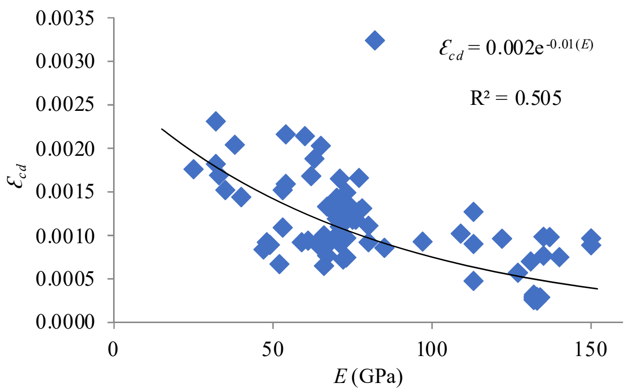

Figure 6. $\mathcal{E}_{cd}$ and elastic modulus (E)

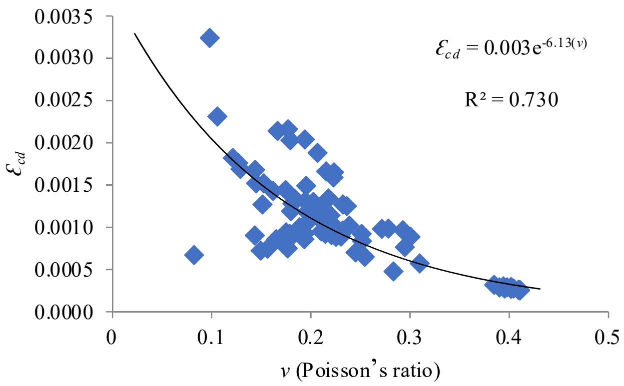

Figure 7.** $\mathcal{E}_{cd}$ **and Poisson's ratio (v)

The relationships between the strain and strength parameters show negative exponential form of functions. As one property value increases the other decreases. However, the relationships show that the strength parameters are independent of the strain property.

4.1.3. Maximum axial strain and strength parameters

The maximum axial strain ($\mathcal{E}_{af}$) values is compared with the strength parameters. The comparisons show different relationships between the strain and the strength parameters (Fig. 8 – 10). The maximum axial strain ($\mathcal{E}_{af}$) is weakly related with the *UCS* (Fig. 8) but stronger relationship is shown with the ratio of *E/UCS* with correlation coefficient of 0.84 (Fig. 9). The *E* and *E/UCS* show negative exponential form of relationships while *UCS* has linear relationship with the strain ($\mathcal{E}_{af}$).

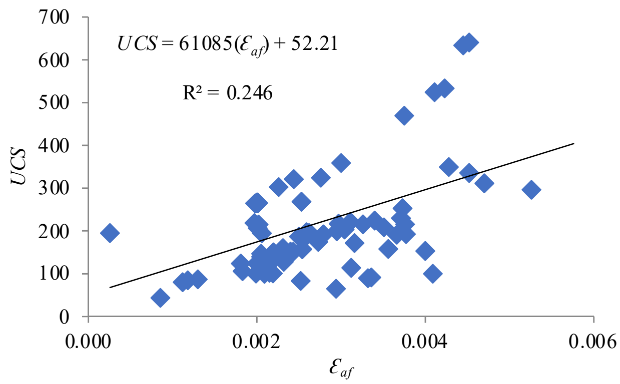

***Figure 8.** UCS and* $\mathcal{E}_{af}$

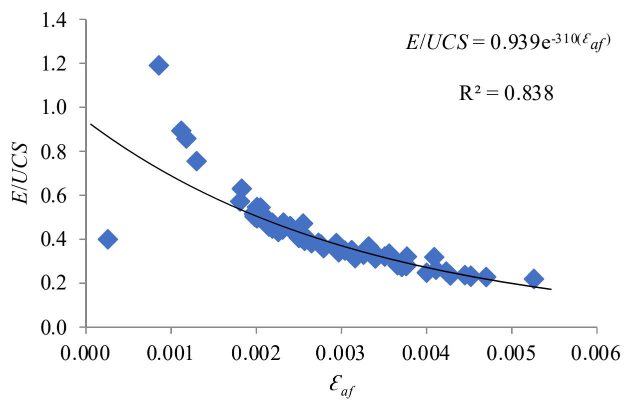

***Figure 9.** E/UCS and* $\mathcal{E}_{af}$

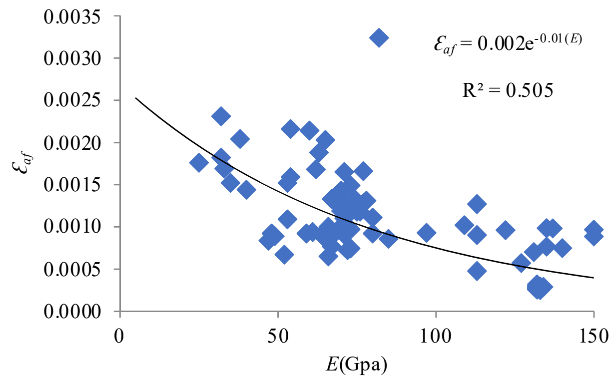

Figure 10.** $\mathcal{E}_{af}$ **and elastic modulus (E)

As the ratio of *E/UCS* increases the maximum axial strain decreases by exponential form of the equation. It can therefore be assumed that rocks with lower ratio of *E/UCS* will induce larger maximum axial strain at strength failure than rocks with higher ratio *E/UCS*. Thus, the lower the ratio of *E/UCS* of rock, the more deformed the specimen at strength failure. Hence rocks with lower *E/UCS* ratio will constitute higher structural instability or elastic instability at strength failure. So, the structural instability of rocks depends on *E/UCS* ratio. Similarly, as shown in the above section between the strength parameters (*E* and *v*) and $\mathcal{E}_{cd}$, also the relationship between *E* and $\mathcal{E}_{af}$ show that the strength parameters are independent while the strain property is dependent (Fig. 10).

4.1.4. Slope of linear elastic deformation of the axial strain curve and strength parameters

The slope of linear elastic deformation of the axial strain curve (θ) is compared with the strength parameters. The slope of linear elastic deformation of the axial strain curve shows direct relationships with the *E* and *v* while the *UCS* shows weak positive exponential relationship (Fig. 11 – 13).

As θ increases the strength parameters increases. The slope of linear elastic deformation of the axial strain curve (θ) is an indication of the elastic stiffness modulus and the ability of the rock to resist deformation or straining. As this strain value increases the strength parameters values also increases which mean that as the ability of rock to resist deformation increases the strength parameters also increases.

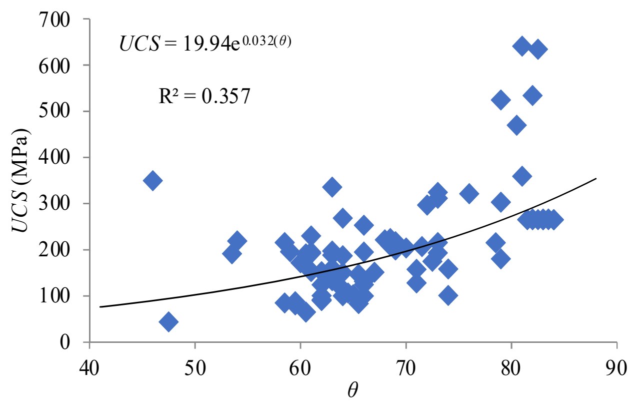

***Figure 11.** UCS and* θ

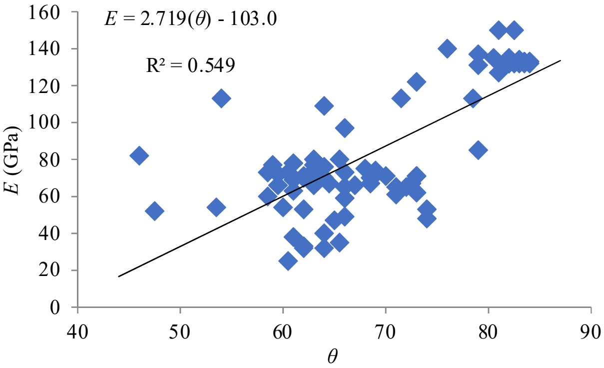

Figure 12. Elastic modulus (E) and θ

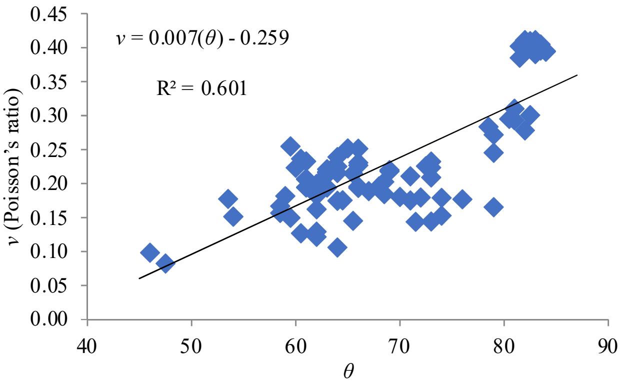

Figure 13. Poisson's ratio (v) and θ

4.2. Strain quantities and elastic stability of strength properties

The strain quantities were compared with the elastic stability of strength properties of the rocks, the compressibility, elastic strain energy and the critical strain criteria for fracture initiation. The purpose of this comparison is to examine the relationship between the strain quantities and the parameters that might influence it stability behaviour. The maximum total volumetric strain does not show any form of relationship with the elastic stability of strength properties of the rocks.

4.2.1. Critical volumetric strain at strength failure and elastic stability of strength properties

The critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) is compared with the elastic strain energy. It shows a positive exponential form of relationship, meaning that as the values of $\mathcal{E}_{vf}$ at strength failure increases so also the elastic strain energy (Fig. 14).

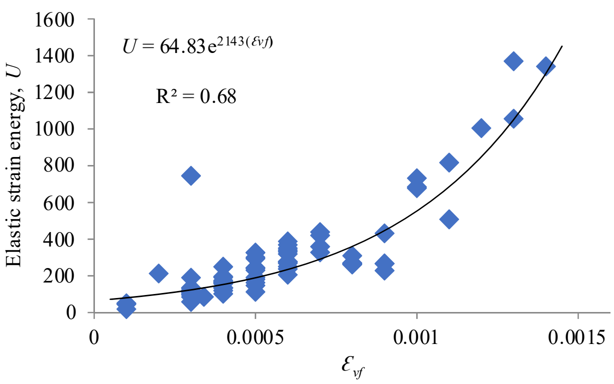

Figure 14. Elastic strain energy (U) and $\mathcal{E}_{vf}$

It can be assumed that as the values of $\mathcal{E}_{vf}$ increases the capacity of rocks to store elastic strain energy increases. It can therefore be stated that rocks with higher ability to accumulate elastic strain energy will induce larger total deformation on the specimen at strength failure. Thus, the higher the stored elastic strain energy in rocks, the more deformed they are at strength failure. So, as the critical volumetric strain at strength failure increases, rocks capacities to store and release elastic strain energy increases and consequently result to violent failure at peak strength. This phenomenon may be compared with rock failure in form of brittle fracture induced by mining. In experimental rock mechanics, it may be compared that failures around the boundaries of an excavation behaves as a rock specimen and the surrounding strata acts as a testing machine. It can be stated that the higher the critical volumetric strain at strength failure, the higher the stored elastic strain energy and the more likelihood of rock burst proneness of the excavation. Hence the higher the critical volumetric strain at strength failure, the higher the stored elastic strain energy and higher the structural instability or elastic instability at failure strength and the more difficult it will be to control.

The critical volumetric strain at strength failure does not show any form of relationship with compressibility. In Figure 15, comparison of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) with critical strain criterion for fracture initiation (e_c) show direct relationship.

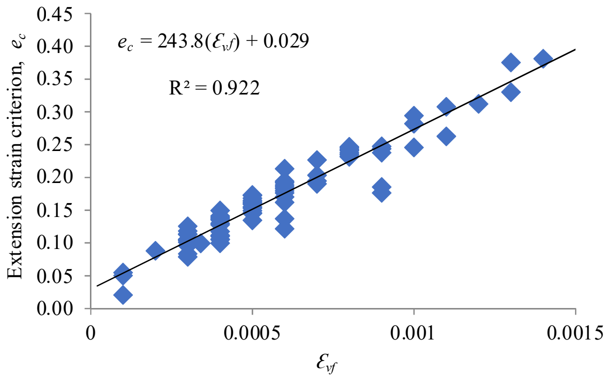

Figure 15. Extension strain criterion (e_c) and $\mathcal{E}_{vf}$

The relationship shows a linear correlation with a strong coefficient of correlation of 0.922. The relationship shows that as the strain values increases so the values of critical strain criterion for fracture initiation. With a strong correlation coefficient of 0.922, it can be suggested that critical volumetric strain at strength failure can be used to estimate the values of critical strain criterion for fracture initiation using the equation connecting them. A plot of critical strain criterion for fracture initiation (e_c) with the *UCS* of the rocks shows that fracture can initiate at very low stress level below 50 MPa (Fig. 16).

Fracture initiation in rock at low stress level can impose untold excavation difficult conditions relating to safety issues, stability of excavation openings, higher extra costs for support requirements and longer construction times. Therefore, the relationship between critical volumetric strains at strength failure ($\mathcal{E}_{vf}$) and critical strain criterion for fracture initiation may improve our understanding of the mechanism of fracture initiation in order to correctly design stable excavations.

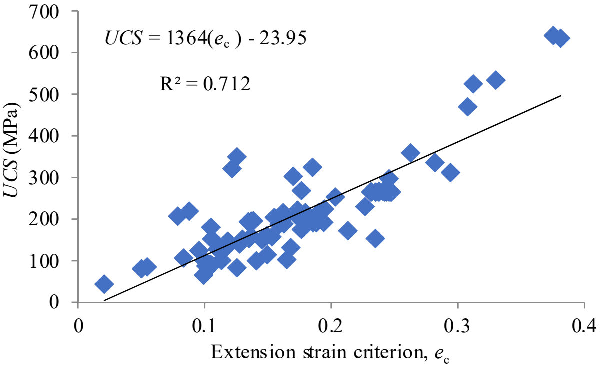

Figure 16. UCS and extension strain criterion (e_c)

4.2.2. Maximum axial strain and elastic stability of strength properties

The comparison of the elastic strain energy (U) with maximum axial strain ($\mathcal{E}_{af}$) shows that as $\mathcal{E}_{af}$ increases also the elastic strain energy increases in positive exponential form (Fig. 17).

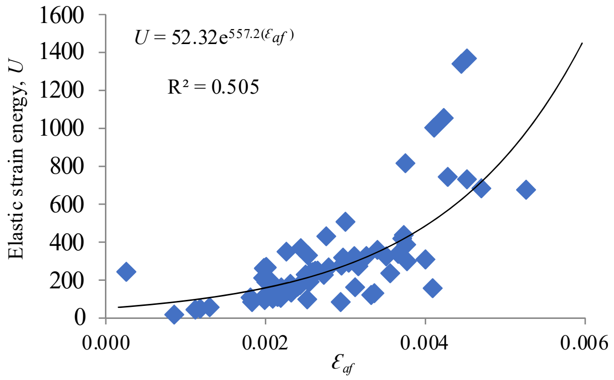

Figure 17. Elastic strain energy (U) and $\mathcal{E}_{af}$

Therefore, rocks with larger values of maximum axial strain might be indicator of its burst proneness in mines since the amount of energy that a particular rock can release at peak strength is an indicator of its burst proneness. The compressibility constant has power form function with the maximum axial strain with a correlation coefficient of 0.72 (Fig. 18). As maximum axial strain increases so also the compressibility, meaning that rocks with higher values of maximum axial strain are more deformed than one with lower maximum axial strain. Therefore, rocks with larger maximum axial strain are likely to pose more stability problems than one with lower maximum axial strain.

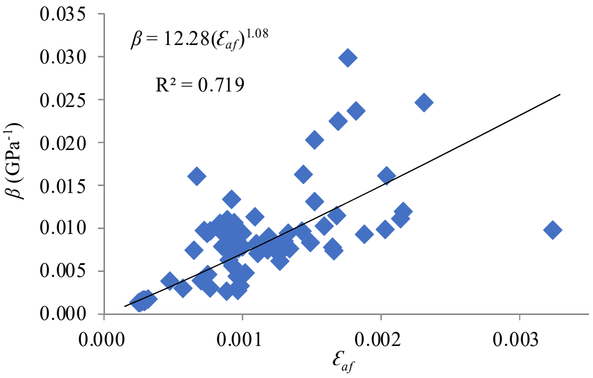

Figure 18. β and $\mathcal{E}_{af}$

4.2.3. Slope of linear elastic deformation of the axial strain curve and elastic stability of strength properties

The slope of linear elastic deformation of the axial strain curve does not show any form of relationship with the elastic strain energy of the rocks. On the other hand, the compressibility and critical strain criterion for fracture initiation are related with the strain by negative exponential and linear functions respectively (Fig. 19, 20).

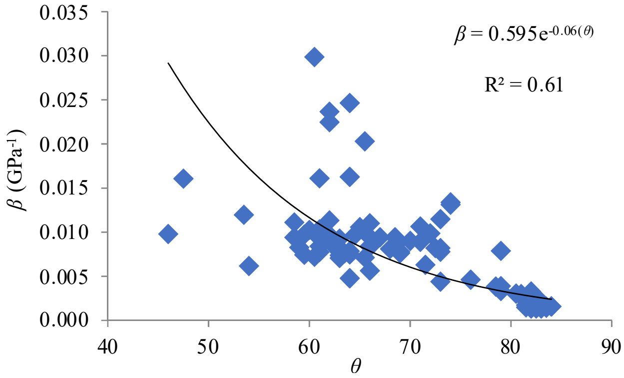

Figure 19. β and θ

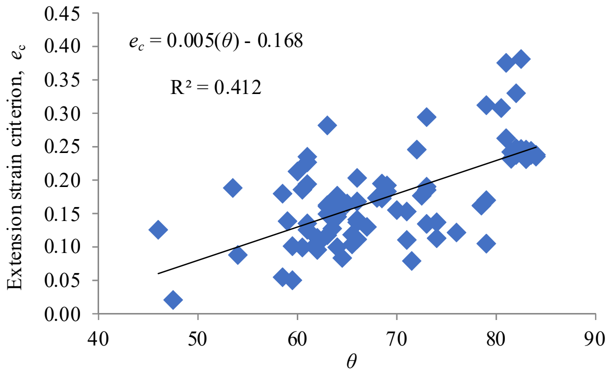

Figure 20. Extension strain criterion e_c and θ

The compressibility or the deformability of the specimen decreases with higher value of θ that is as the ability of rock to resist deformation increases the compressibility of the specimen decreases.

4.3. Strains ratios and strength properties

The ratios of the strains quantities that is the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum axial strain ($\mathcal{E}_{af}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{af}$, the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum total volumetric strain ($\mathcal{E}_{cd}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ and the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ were compared with both the strength parameters and the elastic stability of strength properties of the rocks. The purpose is to show the influence of the strains ratios on the strength properties as compared to the effect of individual strain quantities.

4.3.1. Strains ratios and strength parameters

The ratio of critical volumetric strain at strength failure $\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ show no relationships with

E and *v*. The ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum axial strain ($\mathcal{E}_{af}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{af}$ and the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum total volumetric strain ($\mathcal{E}_{cd}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ show relationships with *E* and *v* (Fig. 21 – 24). The relationships of *E* with $\mathcal{E}_{vf}/\mathcal{E}_{af}$ and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ have linear and logarithmic form of functions with correlation coefficients of 0.63 and 0.64 respectively (Fig. 21, 22). These are higher values than when *E* is compared with individual strains ($\mathcal{E}_{cd}$ and $\mathcal{E}_{af}$) with coefficient of correlations of 0.51 and 0.51 respectively (Fig. 6, 10 and 12) while $\mathcal{E}_{vf}$ does not correlate with *E*. Therefore, the strains ratios are more related to *E* than individual strains. The relationships show that as the ratio of the strains values increases so the values of *E*. The Poisson's ratio is compared with the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum axial strain ($\mathcal{E}_{af}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{af}$.

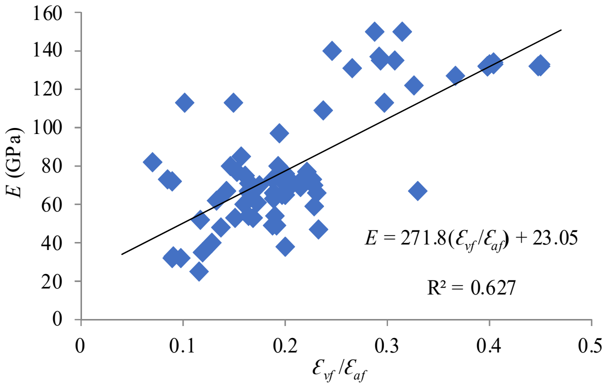

Figure 21. E and $\mathcal{E}_{vf}/\mathcal{E}_{af}$

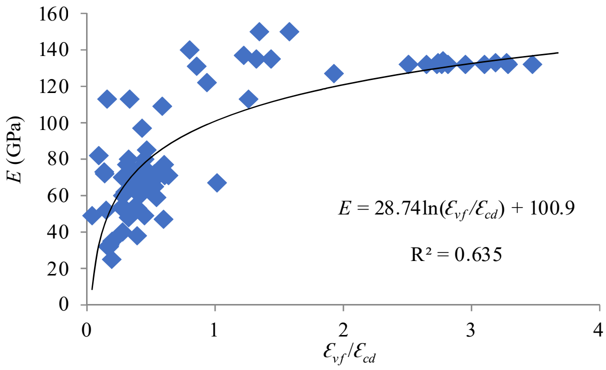

Figure 22. E and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$

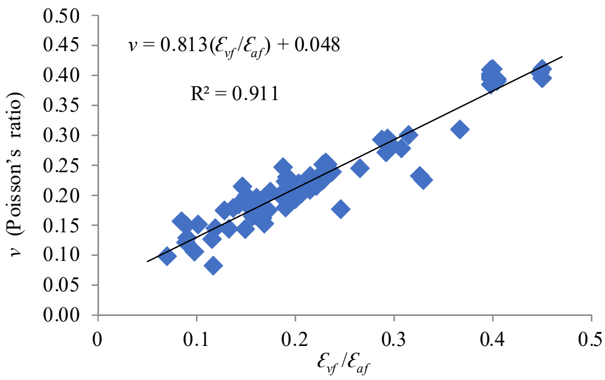

Figure 23. Poisson's ratio (v) and $\mathcal{E}_{vf}/\mathcal{E}_{af}$

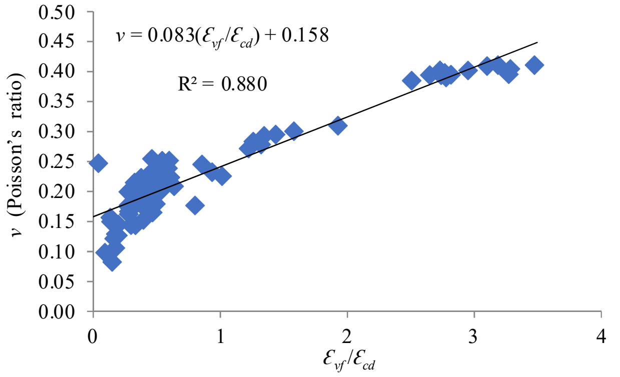

Figure 24. Poisson's ratio (v) and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$

The relationship shows a linear correlation with a stronger coefficient of correlation of 0.911 (Fig. 23). The relationship shows that as the ratio of the strains values increases so the values of Poisson's ratio. With a strong correlation coefficient of 0.911, it may be suggested that Poisson's ratio can be estimated from the strains ratio using the equation connecting them. Similarly, Poisson's ratio is compared with the ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum total volumetric strain ($\mathcal{E}_{cd}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{cd}$. The Poisson's ratio and ratio of critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and maximum total volumetric strain ($\mathcal{E}_{cd}$) i.e. $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ show a linear relationship with a correlation coefficient of 0.88 (Fig. 24). Both relationships between Poisson's ratio and the strains ratios ($\mathcal{E}_{vf}/\mathcal{E}_{af}$ and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$) show stronger correlation coefficients than when compared with individual strain quantities (Fig. 5, 7 and 13). Therefore, Poisson's ratio relates more to the strains ratios than individual strain quantities.

However, the *UCS* and *E/UCS* did not show any form of relationships with the ratios of $\mathcal{E}_{vf}/\mathcal{E}_{af}$ and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ but correlated with the ratio of the critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ (Fig. 25, 26).

The *UCS* show exponential while *E/UCS* logarithmic forms of functions with correlation coefficients of 0.66 and 0.55 respectively. As *UCS* increases exponentially with the strains ratio, the *E/UCS* decreases logarithmically with the strains ratio property values. This value is higher than when *UCS* is compared with θ with correlation coefficient of 0.36 (Fig. 11) while *E/UCS* shows no correlation with θ.

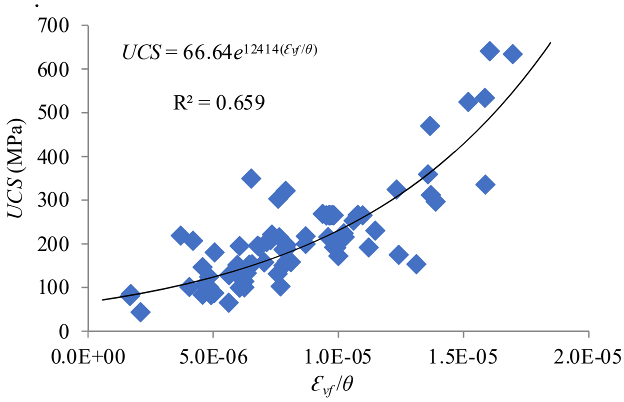

Figure 25. UCS and $\mathcal{E}_{vf}/\theta$

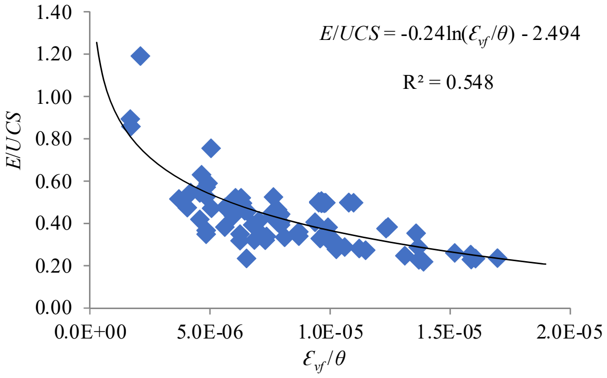

Figure 26. E/UCS and ε_{vf}/θ

Therefore, in all cases the relationships between the strains ratios and the strength parameters are stronger than when compared with individual strain quantities.

4.3.2. Strains ratios and elastic stability of strength properties

The ratio of critical volumetric strain at strength failure (ε_{vf}) and maximum axial strain (ε_{af}) i.e. $\varepsilon_{vf}/\varepsilon_{af}$ and the ratio of critical volumetric strain at strength failure (ε_{vf}) and maximum total volumetric strain (ε_{cd}) i.e. $\varepsilon_{vf}/\varepsilon_{cd}$ were both compared with the compressibility constant (β). The relationships between compressibility constant and the two strains ratios show power form functions. The relationship between compressibility constant and the ratio of $\varepsilon_{vf}/\varepsilon_{af}$ shows slightly higher correlation coefficient (Fig. 27, 28), as the strains ratios increases the compressibility decreases.

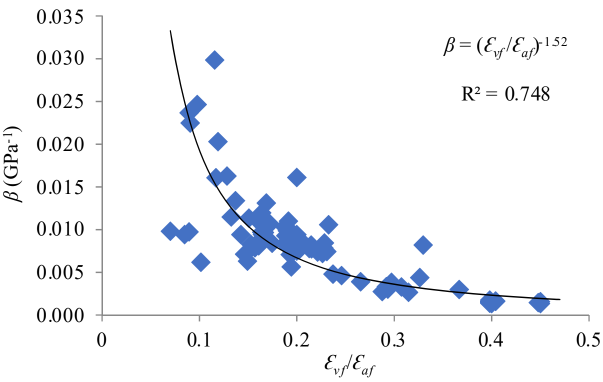

Figure 27. Compressibility constant (β) and $\varepsilon_{vf}/\varepsilon_{af}$

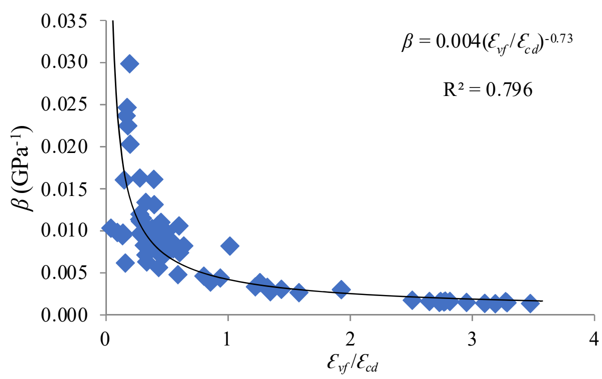

Figure 28. Compressibility constant (β) and $\varepsilon_{vf}/\varepsilon_{cd}$

In both cases the correlation coefficients of the relationships between the strains ratios and compressibility are higher than when compared with individual strain quantities (Fig. 18, 19). As the values of the strains ratios increases the rocks becomes stiff and the bulk modulus increases. The rate at which the compressibility decreases or bulk modulus increases is more rapid with the ratio $\varepsilon_{vf}/\varepsilon_{cd}$ than shown for $\varepsilon_{vf}/\varepsilon_{af}$. The compressibility decreases rapidly from 0.35 to 0.005 from strains ratio ($\varepsilon_{vf}/\varepsilon_{cd}$) 0 to 1 and remain nearly constant to 3.5 of strains ratio ($\varepsilon_{vf}/\varepsilon_{cd}$) (Fig. 28). It can be assumed that the range of rocks deformability or compressibility lies within strains ratio ($\varepsilon_{vf}/\varepsilon_{cd}$) 0 to 1. It can therefore be suggested that the maximum level of rock's deformability or compressibility is 1 under $\varepsilon_{vf}/\varepsilon_{cd}$ vs. compressibility plot. Hence 1 is the threshold limit for which rocks can accommodate compressibility or deformability after which the deformation becomes explosive. Therefore, compressibility with strains ratio $\varepsilon_{vf}/\varepsilon_{cd}$ value above 1 is a precursor to structural instability or elastic instability of rock.

The strains ratios $\varepsilon_{vf}/\varepsilon_{af}$ and $\varepsilon_{vf}/\varepsilon_{cd}$ were both compared with the critical strain criterion for fracture initiation (e_c). The relationships between them show logarithm form of functions. The relationship between critical strain criterion for fracture initiation and the two strains ratios show almost the same correlation coefficients (Fig. 29, 30). The relationships between the strains ratios and critical strain criterion for fracture initiation show that as one property value increase the other increases. The rate at which the critical strain criterion for fracture initiation increases is more rapid with the ratio $\varepsilon_{vf}/\varepsilon_{cd}$ than shown for $\varepsilon_{vf}/\varepsilon_{af}$.

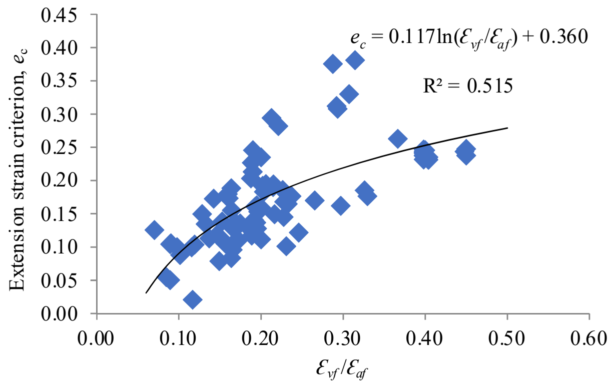

Figure 29. Extension strain criterion e_c and $\varepsilon_{vf}/\varepsilon_{af}$

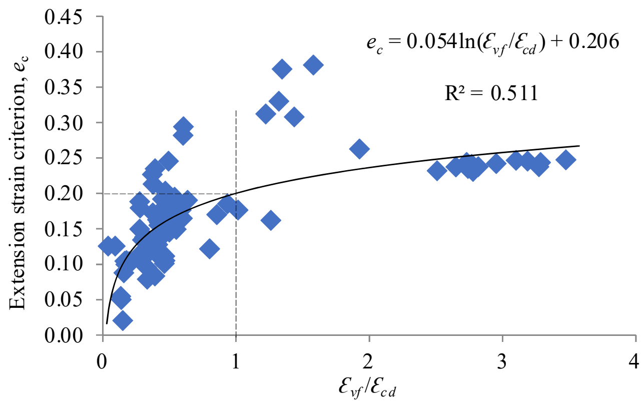

Figure 30. Extension strain criterion e_c and $\varepsilon_{vf}/\varepsilon_{cd}$

The critical strain criterion for fracture initiation increases rapidly from 0 to value of 0.2 for strains ratio $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ from 0 to 1 (Fig. 30). A threshold level of 1 may also be assumed as the limit for fracture initiation above which the rock may suffer brittle fracture failure. Similarly, a critical strain criterion for fracture initiation value of 0.2 may be assumed as the limit after which the rock may experience brittle fracture failure.

This is further examined by plotting critical strain criterion for fracture initiation with the stored elastic strain energy. The plot shows that the accumulated energy increases slowly from 0 to 0.2 of critical strain criterion for fracture initiation up to 300 kJ of stored energy after which the energy accumulate rapidly in exponential form (Fig. 31).

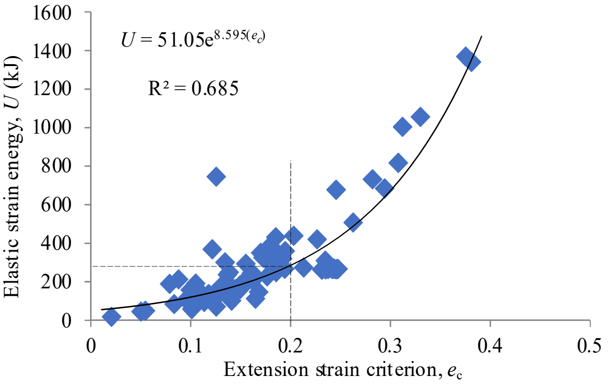

Figure 31. Extension strain criterion e_c and elastic strain energy (U), kJ

It may be assumed that 0.2 of critical strain criterion for fracture initiation or 300 kJ of stored elastic strain energy might be indicator of rock's burst proneness in mines since the amount of energy that a particular rock can release at peak strength is an indicator of its burst proneness. This is further examined by plotting elastic strain energy with the ratio of the critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ (Fig. 32).

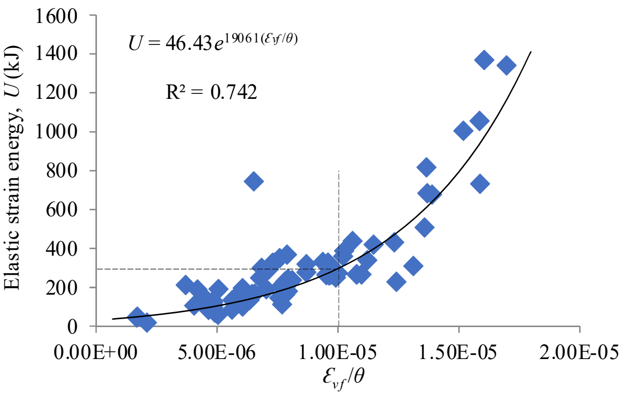

Figure 32. Elastic strain energy (U), kJ and $\mathcal{E}_{vf}/\theta$

Similar result is obtained. The accumulated energy increases slowly from 0 to 1 of the ratio of the critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ up to 300 kJ of stored energy after which the energy accumulate rapidly in exponential form. Also as shown for $\mathcal{E}_{vf}/\mathcal{E}_{cd}$, it may also be assumed that the value of 1 of $\mathcal{E}_{vf}/\theta$ strains ratio may be indicator to burst proneness in mines. The critical strain criterion for fracture initiation is directly related to the ratio of the critical volumetric strain at strength failure ($\mathcal{E}_{vf}$) and slope of linear elastic deformation of the axial strain curve (θ) i.e. $\mathcal{E}_{vf}/\theta$ with stronger correlation coefficient of 0.87 (Fig. 33).

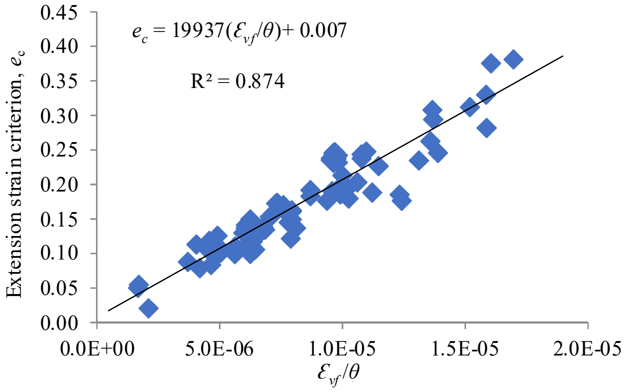

Figure 33. Extension strain criterion e_c and $\mathcal{E}_{vf}/\theta$

5. CONCLUSIONS

The main conclusions of the relationships between strength properties and strain quantities that are associated with the failure-deformation process of hard brittle rocks are as follow:

1. The critical volumetric strain at strength failure is related with the strength parameters (*UCS*, *E/UCS* and *v*). The strain quantity does not show any form of relationship with the elastic modulus (*E*) while it shows linear relation with the *UCS*. As the ratio *E/UCS* increases the critical volumetric strain at strength failure decreases by logarithm form of the equation. The Poisson's ratio shows power form relationship with the strain quantity with a correlation coefficient of 0.467. However stronger relationship is shown with the strains ratios $\mathcal{E}_{vf}/\mathcal{E}_{af}$ and $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ with correlation coefficients of 0.911 and 0.88 respectively. Therefore, Poisson's ratio relates more to the strains ratios than individual strain quantities.

2. The relationships of compressibility constant with the two strains ratios show power form functions. As the strain ratios increases the compressibility decreases. The rate at which the compressibility decreases or bulk modulus increases is more rapid with the ratio $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ than $\mathcal{E}_{vf}/\mathcal{E}_{af}$.

3. The higher the critical volumetric strain at strength failure, the higher the stored elastic strain energy and higher the structural instability or elastic instability at failure and the more likelihood of rock burst proneness.

4. The relationship between critical volumetric strain at strength failure and critical strain criterion for fracture initiation shows a linear correlation with a strong coefficient of correlation of 0.922. The relationship can improve our understanding of the mechanism of fracture initiation in order to correctly design stable structures.

5. The compressibility or the deformability of a rock specimen decreases with higher value of the slope of linear elastic deformation of the axial strain curve (θ). Therefore, as the ability of rock to resist deformation increases the compressibility or the deformability of the specimen decreases. Other properties values show linear relationships with θ.

6. Only elastic modulus and Poison's ratio are related to maximum total volumetric strain ($\mathcal{E}_{cd}$) with negative exponential form. As one property value increases the other decreases. However, the relationships show that the strength parameters are independent of the strain quantity.

7. The maximum axial strain is related with E, E/UCS and $\sigma^2/2E$. The strength properties show exponential relationships with maximum axial strain. However, the relationship between E and $\mathcal{E}_{af}$ show that the strength parameter is independent of the strain quantity. Rocks with larger maximum axial strain might be indicator of its burst proneness in mines since the amount of energy that a particular rock can release at peak strength is an indicator of its burst proneness. The compressibility constant has power form of relationship with the maximum axial strain. As maximum axial strain increases so also the compressibility, meaning that rocks with higher maximum axial strain are more deformed than one with lower maximum axial strain. Therefore, rocks with larger maximum axial strain are likely to pose more stability problems than one with lower maximum axial strain.

8. In all cases the relationships between the strains ratios and the strength parameters are stronger than when compared with individual strain quantities. A threshold level for strains ratio $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ of 1 may be assumed as the limit for fracture initiation above which the rock may suffer brittle fracture failure. The value of strains ratio $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ of 1 is also suggested to be the threshold limit for which rocks can accommodate compressibility or deformability after which the deformation becomes explosive. Therefore, compressibility and critical strain criteria for fracture initiation at strains ratio $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ value above 1 is assumed to be a precursor to structural instability such as flaking, bursting and spalling in excavations.

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МІЦНІСНІ ТА ДЕФОРМАЦІЙНІ ВЕЛИЧИНИ У ПРОЦЕСІ КРИХКОЇ ДЕФОРМАЦІЇ ТВЕРДИХ ГІРСЬКИХ ПОРІД

В.А. Акінбіну, Г.О. Онійіде, П.А. Адесіда

Мета. Вивчення зв'язків між міцнісними характеристиками та величинами деформацій, що виникають у процесі крихкого стискання твердих порід.

Методика. На підставі лабораторних тестів на одноосьове стискання, проведені з 84 видами твердих гірських порід, отримано результати їх міцності на одноосьове стискання, модулі пружності та коефіцієнти Пуассона. Для випробувань використана сервокерована система контролю із замкненим контуром (випробувальна машина MTS 815). Параметри міцності оцінюються відповідно до запропонованих стандартів (Ulusay, 2015).

Результати. Експериментальним шляхом встановлено кореляційні взаємозв'язки критичної об'ємної деформації при втраті міцності з її безпосередніми параметрами (міцність на одноосьове стискання, модуль пружності, коефіцієнт Пуассона). Встановлено, що у всіх випадках взаємозв'язок між відносинами деформації та параметрами міцності сильніший, ніж у порівнянні з окремими величинами деформації. Граничний рівень для деформаційного співвідношення $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ може бути прийнятий як межа початку руйнування, вище якої гірська порода може піддаватися крихкому руйнуванню.

Наукова новизна. Попередні дослідження були сфокусовані у більшості випадків при вивченні напружень розриву (σ_{cd}) та одноосьовому компресійному стисканні (σ_c) характерних рівнів напружень під час стискання й носили теоретичний характер. У цій статті експериментальним шляхом були уточнені результати дослідження співвідношень і взаємозв'язків між міцнісними характеристиками та величинами деформації у процесі деформації твердих гірських порід.

Практична значимість. Встановлені співвідношення міцнісних та деформаційних величин сприяють удосконаленню знань щодо коректної оцінки стійкості проведених гірничих виробок, проектування стійких споруджень, таких як тунелі, розробки в гірництві, промисловому та цивільному будівництві.

Ключові слова: *співвідношення, деформаційний процес, крихкі тверді гірські породи, міцнісні характеристики, стійкість споруджень*

ПРОЧНОСТНЫЕ И ДЕФОРМАЦИОННЫЕ ВЕЛИЧИНЫ В ПРОЦЕССЕ ХРУПКОЙ ДЕФОРМАЦИИ ТВЕРДЫХ ГОРНЫХ ПОРОД

В.А. Акинбину, Г.О. Онийиде, П.А. Адесида

Цель. Исследование взаимосвязей между прочностными характеристиками и величинами деформаций, возникающими в процессе хрупкого сжатия твердых хрупких пород.

Методика. На основе лабораторных тестов на одноосное сжатие, проведенных с 84 видами твердых горных пород, получены результаты их прочности на одноосное сжатие, модуля упругости и коэффициента Пуассона. Для испытаний использовалась сервоуправляемая система контроля с замкнутым контуром (испытательная машина MTS 815). Параметры прочности оценивались в соответствии с предложенными стандартами (Ulusay, 2015).

Результаты. Экспериментальным путем установлены корреляционные взаимосвязи критической объемной деформации при потере прочности с ее непосредственными параметрами (прочность на одноосное сжатие, модуль упругости, коэффициент Пуассона). Установлено, что во всех случаях взаимосвязь между отношениями деформации и параметрами прочности сильнее, чем по сравнению с отдельными величинами деформации. Пороговый уровень для деформационного соотношения $\mathcal{E}_{vf}/\mathcal{E}_{cd}$ может быть принят как граница начала разрушения, выше которой горная порода может подвергаться хрупкому разрушению.

Научная новизна. Предыдущие исследования были сфокусированы в большинстве случаев на изучении напряжения разлома (σ_{cd}) и одноосном компрессионном сжатии (σ_c) характерных уровней напряжения во время сжатия и носили теоретический характер. В этой статье экспериментальным путем были уточнены результаты исследования соотношений и взаимосвязи между прочностными характеристиками и величинами деформации в процессе деформации твердых горных пород.

Практическая значимость. Установленные соотношения прочностных и деформационных величин способствуют совершенствованию знаний относительно корректной оценки устойчивости проведенных горных выработок, проектированию устойчивых сооружений, таких как туннели, разработки в горном деле, промышленном и гражданском строительстве.

Ключевые слова: *соотношения, деформационный процесс, хрупкие твердые горные породы, прочностные характеристики, устойчивость сооружений*

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