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Loading rate conditions and specimen size effect on strength and deformability of rock materials under uniaxial compression

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Abstract

In this study, various rock and cementitious rock-like material specimens with same ratio of length to diameter and different sizes were tested under various deformation controlled loading rate (mm/min) and load controlled rate (kN/s) conditions. According to the results obtained from 93 specimens of 5 different types of rock material and 2 different rock-like materials (cement paste and a concrete mix including sand) tested in this study, uniaxial compressive strength (UCS) values were found to significantly decrease with an increase in the specimen size under the condition of a load controlled rate (kN/s) selection. To practically remove the size effect on UCS values, the uniaxial compression test is suggested to perform selecting the loading rate as strain controlled (s^{-1}) and proportional to diameters of specimens with different sizes and same geometry. In addition to the UCS values, Modulus of elasticity values, stress and strain graph shapes and deformation characteristics were found to significantly change with the change of the specimen size and loading rate. According to the results, both modulus of elasticity values and brittleness were found to notably increase as a result of increase in loading rate values.

Keywords: Uniaxial compressive strength, Modulus of elasticity, Rock core size, Loading rate, Specimen geometry

Introduction

Determination of the uniaxial compressive strength (UCS), one of the most crucial inputs in rock engineering design works is detailed in different standards and suggestions by the International Society for Rock Mechanics and Rock Engineering (ISRM). The relevant standards and suggestions include some statements to select appropriate values of different parameters like geometry, size and loading rate. As ideal geometry of the UCS test specimens, length to diameter (L/D) ratio of the cylindrical specimens is suggested to be 2–2.5 by ASTM (American Society for Testing and Materials) and TSE (Turkish Standards Institution). On the other hand, the ratio should be 2.5–3 according to ISRM suggestions [1–3]. The geometry effect on the UCS values is one of the well-studied topics in rock testing. It is known that an increase in the ratio of length to diameter of the cylindrical core specimens make strength values to decrease [4–6].

The specimen size has also a significant effect on the UCS test results that an increase in the size makes a decrease in the UCS values [7–9]. Stress concentration at the crack

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initiation location in the specimens increases with an increase in the size under a same load per a contact area condition. That situation is a significant reason making bigger specimens to fail under lower measured strength values in comparison with smaller size specimens [10–12]. In the UCS tests of rock materials, the loading rate is many times load control selected with the unit of kN/s. It is known that the increase in the loading rate makes also an increase in the UCS values [13–17]. Big size specimens tested under a same load controlled rate (kN/s) have lower deformation rates (mm/min) and strain rates (s^{-1}) which cause to measure lower UCS values than those of the specimens with smaller sizes. From this point of view, it can be inferred that a relatively high loading rate should be selected to not have a decrease in the UCS values in case of increase in the specimen size.

In this study, different size rock core specimens and cementitious rocklike materials were tested to investigate whether the size effect on UCS values can be eliminated by loading under an appropriately changed loading rate selection. In addition to the UCS values, changes in the modulus of elasticity values and deformation characteristics of different rock and rocklike specimens were determined to investigate variations in the uniaxial deformability test results with the change of the size and loading rate conditions.

Materials and methods

To prepare rock specimens with different sizes, core cutters with the inner diameters of 32 mm and 54.7 mm (NX size) were used (Fig. 1). All of the rock core specimens were cut to have a same length to diameter ratio of 2 by using sawing machines (Fig. 2). The end faces of the cores and rock-like cementitious samples were smoothened to maintain precision within 0.02 mm and made perpendicular to the sample axis within 0.05 mm using comparator. A total of 75 rock core samples were prepared and used in triplication for each testing condition of size and loading rate. Totally, five different rock materials (Limestone, Tuff, Siltstone, Dacite, Akarsen mine ore) were tested for the present study. All the rock materials tested in this study were taken from the vicinity of Akarsen copper mine, an underground mine in Artvin city of Turkey.

Size effect of the rock specimens were investigated under both load controlled rate (kN/s) and deformation controlled rate (mm/min) conditions. To load under various rate unit selection conditions, two different equipments with hydraulic and electrical motor presses were used. A linear variable differential transformer (LVDT) was used

Fig. 1 Coring process by using drill bits with diameters of 32 mm (**a**) and 54 mm (**b**), different size core drillers (**c**)

Fig. 2 Core cutting

in tests with the deformation controlled rate condition. In deformation controlled tests, different size specimens were tested under both a same deformation per time rate (mm/min) and strain rate (s^{-1}) values which are proportional to the lengths of specimens. In case of supplying same deformation per time rate (mm/min) for specimens with different sizes, strain rates were inversely proportional to the specimen lengths. For instance, 54/32 times higher strain rate in the unit of s^{-1} was made for core specimens with 32 mm diameter by selecting same deformation rate (mm/min) with that of the specimens having the diameter of 54 mm. On the other hand, strain rates were selected directly proportional to specimen lengths in the other testing case under deformation controlled rate selection. By this way, two different strain rate conditions which are directly and inversely proportional to ratio between lengths of different size specimens were supplied in deformation controlled tests (Tables 1, 2). In the tests with load controlled rate selection, the rate was chosen to be 1.0 kN/s.

Two different cementitious mixes were prepared as rocklike material specimens. The first group rocklike materials (Rocklike 1) included 350 kg/m^3 cement, 1675 kg/m^3 aggregate, 180 kg/m^3 water. Maximum particle size of the aggregate used in this study is 8 mm. Rocklike 1 type material specimens were cured for 3 days before testing. As the second group rock-like material (Rocklike 2), homogeneous cement paste specimens without aggregate content were prepared. Because specimens with a small diameter of 27 mm were used in the test of second group rocklike material, aggregate was not used in the mix since it was thought to cause failure mechanism invalidity. Ordinary Portland cement (OPC) and water were mixed thoroughly in a mixer for 8 min to make homogenization of Rocklike 2 specimens. Similarly, the mix of Rocklike 1 content was homogenized in a tank mixer for 8 min.

Table 1 Rock strength results obtained from tests with deformation controlled rate (UCS: uniaxial compressive strength, D: diameter, H: height, SN: specimen number, SD: standard deviation)

Material	Size	Def. rate (mm/min)	Strain rate (s^{-1})	UCS (MPa)	SN	SD (MPa)
Limestone	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	18.8	3	0.7
Limestone	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	20.9	3	0.5
Limestone	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	19.5	3	0.6
Tuff	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	11.6	3	0.8
Tuff	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	12.9	3	0.9
Tuff	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	12.2	3	0.7
Siltstone	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	18.1	3	0.6
Siltstone	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	22.0	3	0.8
Siltstone	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	18.4	3	0.5
Akarsen ore	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	12.7	3	0.7
Akarsen ore	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	14.5	3	0.6
Akarsen ore	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	13.4	3	0.8

Table 2 Rocklike material strength results obtained from tests with deformation controlled rate

Material	Size	Def. rate (mm/min)	Strain rate (s^{-1})	UCS (MPa)	SN	SD (MPa)
Rocklike 1	D: 100 mm, H: 200 mm	1.00	8.33×10^{-5}	5.56	5	0.22
Rocklike 1	D: 54 mm, H: 108 mm	1.00	1.54×10^{-4}	6.06	5	0.17
Rocklike 1	D: 54 mm, H: 108 mm	0.29	4.48×10^{-5}	5.51	5	0.23
Rocklike 2	D: 54 mm, H: 108 mm	1.00	1.54×10^{-4}	14.03	3	0.44
Rocklike 2	D: 54 mm, H: 108 mm	0.48	7.4×10^{-5}	12.84	3	0.35
Rocklike 2	D: 26 mm, H: 52 mm	0.48	1.54×10^{-4}	15.17	3	0.40
Rocklike 2	D: 26 mm, H: 52 mm	0.23	7.4×10^{-5}	14.49	3	0.29

Rocklike specimens were cast into moulds with different diameters of 100 mm, 54 mm, 27 mm and diameter to length ratio of 2 (Fig. 3). The cementitious mixes were cast into the moulds in three steps, and air was removed with tamping rods after each casting steps. The moulded specimens were also put on the vibration table for 1 min to remove air bubbles and increase homogeneity.

In this study, uniaxial compressive strength (UCS) and deformability properties of various rock and rocklike materials were investigated under the effect of changing size and loading rate conditions. Some photos from tests of rock and rock-like specimens with different sizes are given in Figs. 4 and 5.

Results

Strength results obtained from tests with load controlled and deformation controlled rates are given in Tables 1, 2, 3 and 4 which also include the details of loading rate values under different test conditions. Additionally, variations in strength values under different size and loading rate conditions are given in Figs. 6 and 7. As seen in Table 4, the ratio between strength values obtained from bigger and smaller specimens (UCS_b/USC_s) changed within a small range of 5% in case of selecting the strain rate as length

Fig. 3 Molded cementitious mixes: Rocklike 1 (**a**) and Rocklike 2 (**b**) specimens

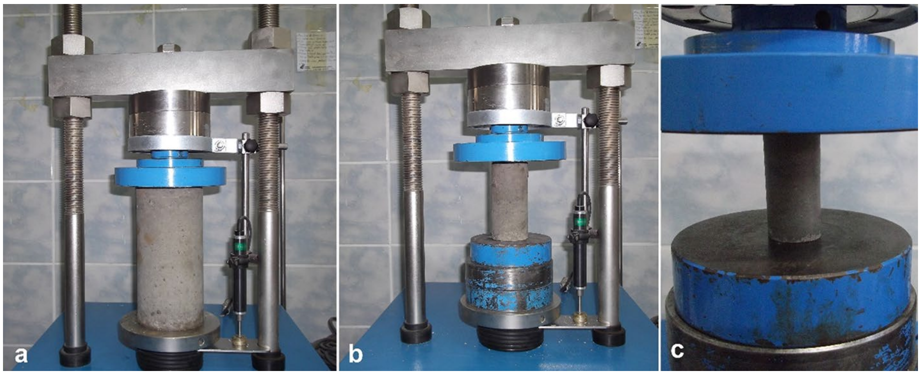

Fig. 4 Testing strengths of rocklike specimes with different diameters of 100 mm (**a**), 54 mm (**b**) and 26 mm (**c**)

proportional. Therefore, it can be inferred that the size effect on UCS values can be practically neglected selecting strain rate proportional to lengths of specimens.

Strains of specimens were not measured in tests with load controlled rate selection. On the other hand, both strength and deformability parameters were determined under the tests carried out with deformation controlled rate selection. According to the stress and strain graphs drawn by the loading equipment program, secant modulus of elasticity (E_{sec}) and tangent modulus of elasticity (E_{tan}) values were calculated as given in Table 5. To calculate the modulus of elasticity values, methodology suggested by the ISRM [1] was followed. Average modulus of elasticity values were not calculated since it is not usable for comparison of different loading conditions as stress strain graphs are linearized under different stress levels for different specimens.

As seen in Figs. 8 and 9, modulus of elasticity values were found to increase with increasing loading rate. Besides, stress strain graph shapes of all the materials tested

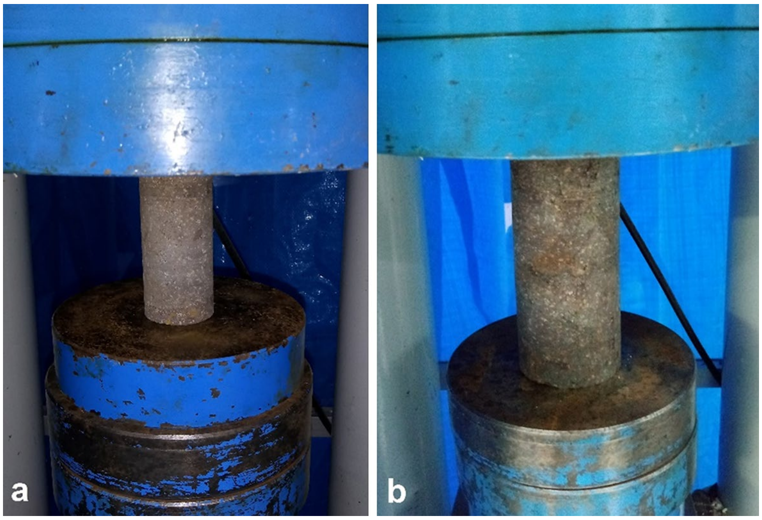

Fig. 5 Testing strengths of rock specimes with different diameters of 32 mm (**a**), 54 mm (**b**)

Table 3 Results of tests with load controlled rate selection

Material	Size	Load rate (kN/s)	UCS (MPa)	SN	SD (MPa)
Limestone	D: 54 mm, H: 108 mm	1.0	18.3	3	0.5
Limestone	D: 32 mm, H: 64 mm	1.0	22.4	3	0.6
Tuff	D: 54 mm, H: 108 mm	1.0	10.6	3	0.6
Tuff	D: 32 mm, H: 64 mm	1.0	13.8	3	0.7
Siltstone	D: 54 mm, H: 108 mm	1.0	17.2	3	0.9
Siltstone	D: 32 mm, H: 64 mm	1.0	24.3	3	0.8
Dacite	D: 54 mm, H: 108 mm	1.0	49.7	3	1.3
Dacite	D: 32 mm, H: 64 mm	1.0	62.4	3	1.5
Akarsen ore	D: 54 mm, H: 108 mm	1.0	13.2	3	1.0
Akarsen ore	D: 32 mm, H: 64 mm	1.0	17.5	3	0.9

Table 4 Strength relations obtained under the condition of strain rate values selected as proportional to specimen heights (UCS_b: uniaxial compressive strength of big specimens, USC_s: uniaxial compressive strength of small specimens)

Material	Strength ratios (UCS_b/USC_s)	Height of big size specimens	Height of small specimens
Limestone	0.96	108	64
Tuff	0.95	108	64
Siltstone	0.98	108	64
Akarsen ore	0.95	108	64
Rocklike 1	1.01	200	108
Rocklike 2	0.97	108	52

in this study were determined to significantly differ with the change in load conditions that the specimens were found to be fail with a more brittle characteristic as a result of increase in loading rate values. Some stress–strain graphs given as example for the

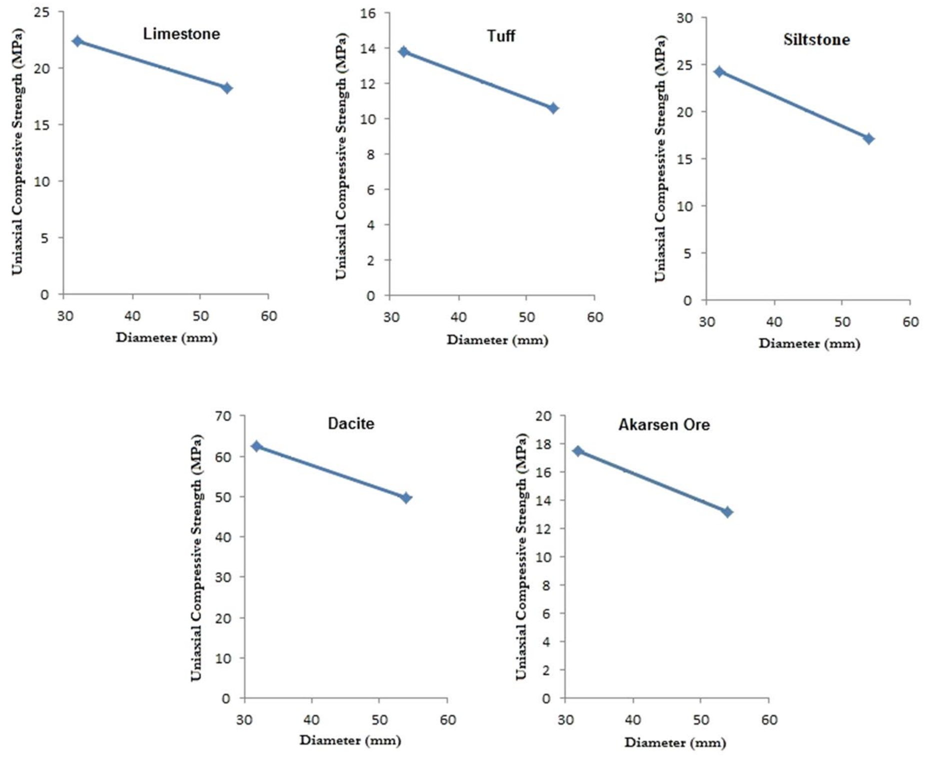

Fig. 6 UCS values under same load rate (kN/s)

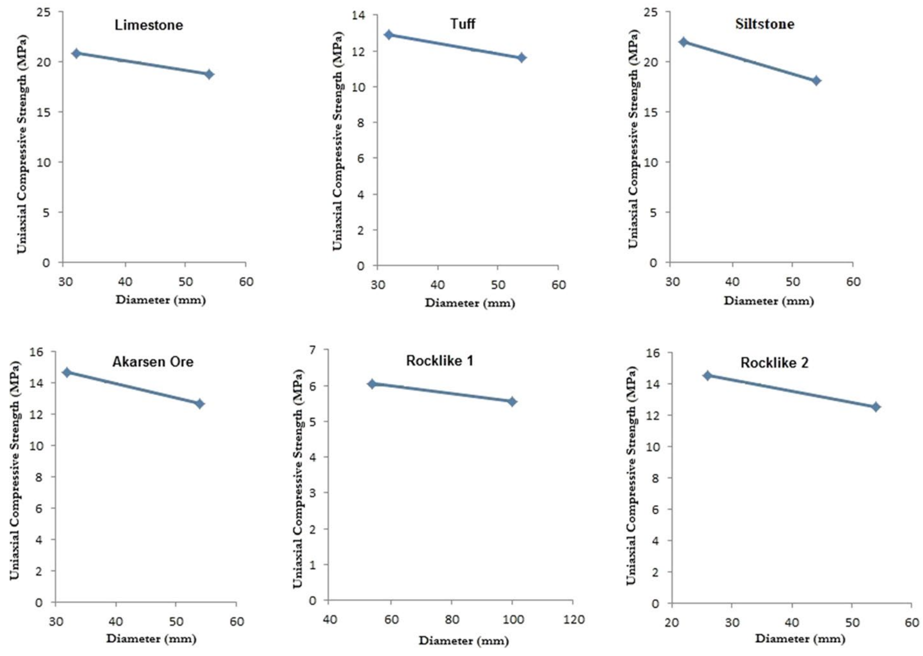

Fig. 7 UCS values under same deformation rate (mm/min)

Table 5 Deformation modulus values (E_{sec}: secant modulus of elasticity, E_{tan}: tangent modulus of elasticity)

Material	Size	Def. rate (mm/min)	Strain rate (s^{-1})	E_{sec} (GPa)	E_{tan} (GPa)
Limestone	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	9.32	11.53
Limestone	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	8.87	11.09
Limestone	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	8.06	10.35
Tuff	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	7.44	9.61
Tuff	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	6.90	8.98
Tuff	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	6.31	8.64
Siltstone	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	9.53	10.77
Siltstone	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	10.22	12.86
Siltstone	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	8.98	11.43
Akarsen ore	D: 54 mm, H: 108 mm	0.54	8.33×10^{-5}	9.69	11.90
Akarsen ore	D: 32 mm, H: 64 mm	0.54	1.41×10^{-4}	8.75	10.06
Akarsen ore	D: 32 mm, H: 64 mm	0.19	4.95×10^{-5}	7.39	9.31
Rocklike 1	D: 100 mm, H: 200 mm	1.00	8.33×10^{-5}	1.40	2.78
Rocklike 1	D: 54 mm, H: 108 mm	1.00	1.54×10^{-4}	0.83	1.49
Rocklike 1	D: 54 mm, H: 108 mm	0.29	4.48×10^{-5}	0.61	1.02
Rocklike 2	D: 54 mm, H: 108 mm	1.00	1.54×10^{-4}	1.82	2.73
Rocklike 2	D: 54 mm, H: 108 mm	0.48	7.4×10^{-5}	1.54	2.45
Rocklike 2	D: 26 mm, H: 52 mm	0.48	1.54×10^{-4}	2.24	3.34
Rocklike 2	D: 26 mm, H: 52 mm	0.23	7.4×10^{-5}	1.91	2.53

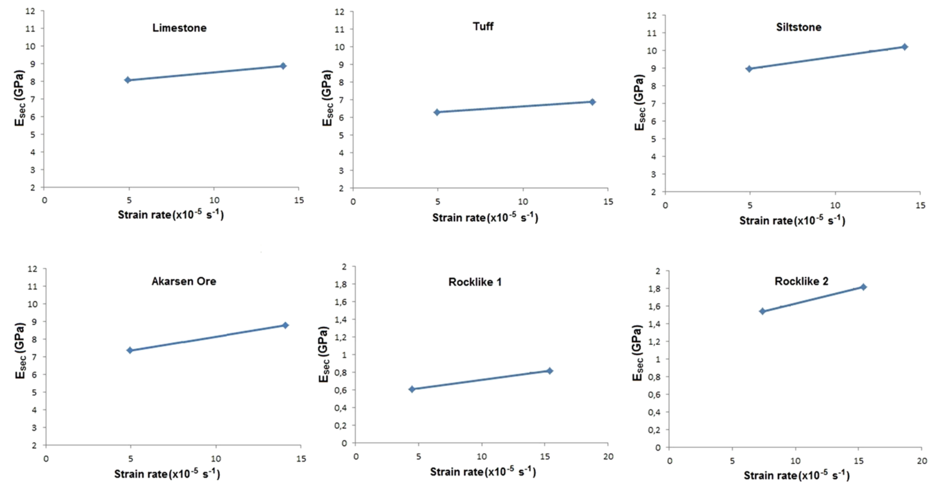

Fig. 8 Secant modulus of elasticity values

change in brittleness with variations in strain rate values are shown in Fig. 10. As a result of the increase in the brittleness with increasing in strain rate, failure shapes were also differed. As a remarkable failure variation with the change of strain rate, limestone specimens exhibited a failure with throwing particles and crumbling parts under the high strain rate of $1.41 \times 10^{-4}\ s^{-1}$, whereas limestone specimens loaded under low strain rate value of $4.95 \times 10^{-5}\ s^{-1}$ failed with one narrow crack (Fig. 11).

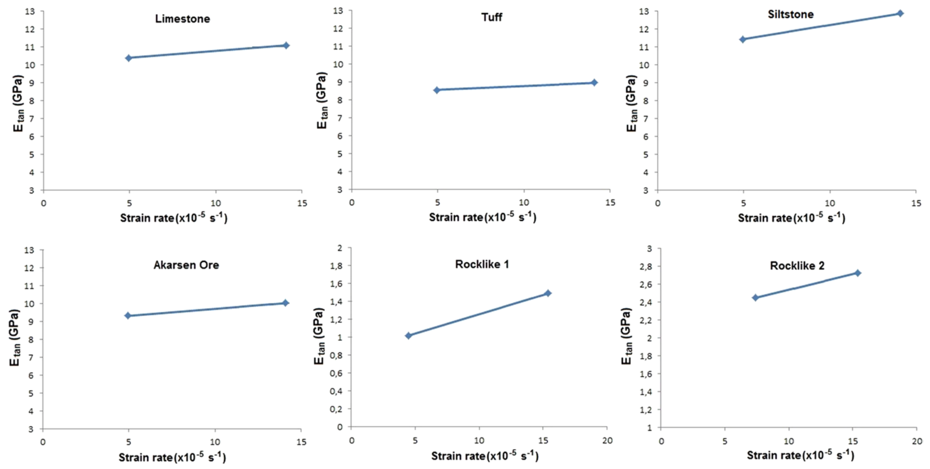

Fig. 9 Tangent modulus of elasticity values

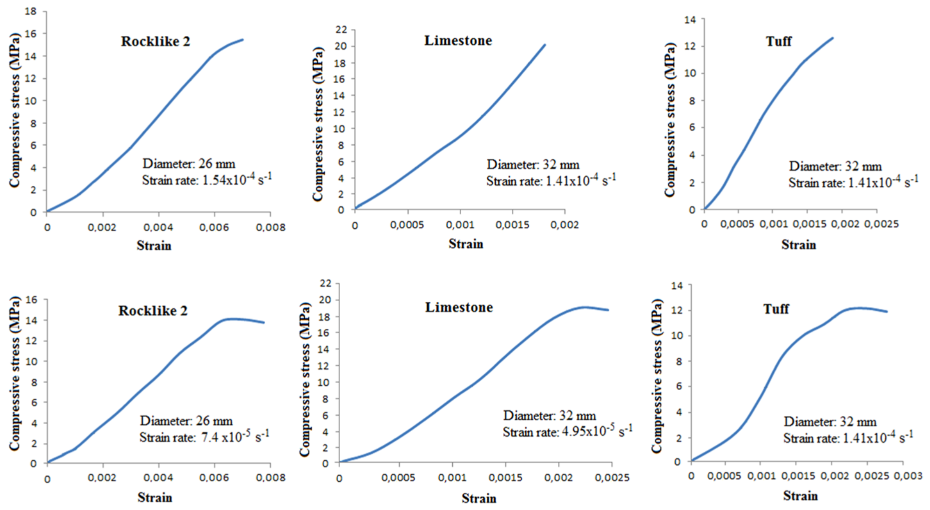

Fig. 10 Some stress–strain graphs

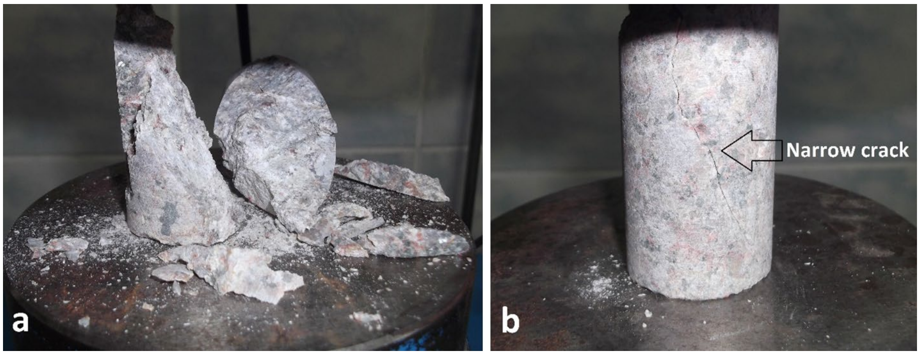

Fig. 11 An example for variation in failure under different strain rates: Limestone specimens tested under different strain rates of 1.41 × 10^{-4} s^{-1} (**a**) and 4.95 × 10^{-5} s^{-1} (**b**)

Discussions and conclusion

Finding the increase of the UCS values with an increase in loading rate is parallel with the results obtained from other previous studies carried out by different researchers [13–17]. Under a load controlled rate (kN/s), change in the size causes also a change in the strain rate (s^{-1}) that a decrease of the size makes an increase in the rate value. Therefore, UCS values measured from smaller size specimens are higher than those of bigger ones.

The size effect was assessed to be not ignorable under the conditions of both load controlled and deformation controlled rates [18–20]. However, it should be noted herein that the size effect was found to be considerably minimized by testing under a same deformation rate condition in comparison with a load controlled rate selection. To practically remove the size effect, strain controlled loading rate (s^{-1}) selected to proportionally increase with the change in specimen lengths was found usable. For instance, in case of increase in rock core specimen length from 64 mm to 108 mm, strain rate should be increased 108/64 times in comparison to the rate in test of the small specimen. In this study, core diameters of 32 mm and 54 mm were compared to investigate a 1.7 times change in size of the core specimens with the ratio of length to diameter of 2. Therefore, findings of this study should be considered for that kind of size variation and not be used for generalization since relation between UCS values can change for different variations in specimen sizes [21–23].

The size and loading rate have significant effect not only for strength values but also on deformability properties of rock and rocklike materials. The modulus of elasticity values were found to increase with increasing in loading rate as similar with results of other studies [24–26]. As another significant observation from this study, brittleness of rock and rocklike materials was determined to increase with an increase in loading rate. This situation confirms that more energy absorption is needed to make the start of cracking as the loading rate increases and the increase in energy absorption under the elastic deformation limit makes more rapid crack propagation and immediate failure as the plastic deformation starts [27–29].

In conclusion, the loading rate was found to significantly change strength and deformability properties of rock and cementitious rocklike materials that the increase in loading rate made increases in both UCS and modulus of elasticity values and the brittleness. As the most notable outcome of this study, the loading rate is suggested to select as strain controlled and proportional to diameters of specimens with different sizes to practically eliminate the size effect on the UCS values.

Authors' contributions

The author read and approved the final manuscript.

Competing interests

The author declares that he has no competing interests.

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