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Research article

The effect of anisotropy on the mechanical properties of artificial rock mass based on laboratory physical modeling

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Specimen size
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Abstract

Assessment of strength anisotropy has been one of the most challenging subjects in rock mechanics and civil engineering. The orientation of the discontinuity plane, the aggregate distribution, and the specimen size have a significant influence on the mechanical properties of rock and cementitious materials. This study aims to evaluate the effect of anisotropy on uniaxial compressive strength, elastic constants, and destruction-specific energy using physical modeling. For this purpose, different concrete blocks were produced in which aggregate sizes of 9.5, 12.5, and 19 mm were used. Different cylindrical specimens with diameters of 45, 69, and 94 mm were prepared. A suite of laboratory testing was performed on prepared concrete samples as a function of discontinuity plane angle (α=30°,45°, and 60°), including uniaxial compressive strength and deformability tests. The results obtained have shown that the mechanical properties of cementitious materials have different values concerning the banding plane, aggregate size, and specimen volume. It was shown that the uniaxial compressive strength and tangent modulus of elasticity show the highest values in low discontinuity plane angle than those obtained in the other directions. However, in concrete mixtures with a grain size of 0-19 mm, an increasing-decreasing trend of strength behavior was observed with ascending the orientation of the discontinuity plane from 30° to 60°. The findings presented indicated that with increasing aggregate size, strength properties descend due to the rise in heterogeneities that affect failure modes. Finally, it was revealed that when specimen size increases from 69 to 94 mm in diameter, led to significant rises in the values of compressive strength and elasticity modulus in cementitious materials.

1. INTRODUCTION

It is well-known that for most engineering designs, the determination of mechanical properties and fracture behavior is of critical importance. The strength of rock and concrete material and their fracture behavior are a function of the mineralogical composition, matrix, specimen size, grain size, specimen geometry, loading rate, grain arrangement, moisture content, density, porosity, micro-cracks and internal fractures, and characteristics of discontinuities (frequency, orientation, spacing, aperture, and filling) [1-5]. Anisotropy and heterogeneity affect the failure process and play a significant role in the design of engineering structures. The importance of anisotropy in rock mechanics and civil engineering depends mainly on the relative size of the problem concerning the size of the rock and concrete features. Further, the anisotropy type, which is critical to the engineering project, may vary from one scale to the next [6-8].

Over the past century, many investigations (Sabnis and Mirza [9]; Allirot and Boehler [10]; Hoek and Brown [11]; Bazant and ASCE [12]; Ramamurthy [13]; Carpinteri et al. [14]; Kozul and Darwin [15]; Amadei [6]; Eberhardt et al. [16]; Chen and Liu [17]; Bazant et al. [18]; Elices and Rocco [19]; Seddik Meddah et al. [20]; Ali et al. [21]; Darlington and Ranjith [7]; Ding et al. [22]; Masoumi et al. [23]; Darbor et al. [2]; Faramarzi and Rezaee [1]) have been conducted on the influence of the aggregate size distribution, the orientation of the discontinuity plane, and the specimen volume on uniaxial compressive strength and elastic constants. Despite many attempts that have been undertaken in the past to describe the anisotropy and heterogeneity of various concrete and rock materials, still, the particular concern should be given to the comprehensive understanding of the properties of anisotropic specimens for a safe and reliable design of engineering structures. Also, most previous research to determine the relationship between the orientation of the discontinuity plane with mechanical properties and destruction-specific energy have conducted in rock materials. Few efforts have been made in the field of cementitious materials. All the previous research has shown that the rock strength varies with the anisotropy and heterogeneity. Allirot and Boehler's [10] study on diatomite specimens revealed that the uniaxial compressive strength and overall Young's modulus vary widely in different specimens of the same rock with the different orientation of the discontinuity planes being tested under uniaxial compression. Ali et al. [21] evaluated the strength and deformation anisotropy behavior of rock specimens as a function of foliation plane angle (β). They showed that the minimum failure strength value observes at an orientation angle ranging from 30° to 60°, and the maximum strength is either at β=0° or β=90°. Hoek and Brown [11] concluded that the relative difference between the maximum and the minimum values of uniaxial compressive strength differs from one material type to the other depending on the material anisotropy degree.

The aggregate size of concrete and rock material is one of the most critical microstructural parameters that affect mechanical properties. Sabnis and Mirza [9] noted that the compressive strength of concrete decreases with increasing grain size. Kozul and Darwin [15] investigated the influences of aggregate type, size, and content on concrete uniaxial strength. They exhibited that the strength of concrete samples is only slightly affected by grain size. Eberhardt et al. [16] found that rock strength decreases with increasing aggregate size where longer cracks propagating along more extended planes of discontinuity coalesced at lower stresses. Chen and Liu [17], showed that fracture parameters of high-performance concrete depend on the grain size distribution and the volume fraction of aggregate. Elices and Rocco [19] studied the effects of aggregate size on the mechanical properties of concrete, such as fracture energy, tensile strength, and modulus of elasticity. Their results showed that the tensile strength appeared to decrease with increasing aggregate size. Research by Seddik Meddah et al. [20] revealed that content and particle size distribution (PSD) for concrete specimens is an important issue. Faramarzi and Rezaee [1] investigated the influence of aggregate size and the specimen volume on the mechanical properties of cementitious materials. They found an increase in the aggregate size of concrete specimens until a critical volume of specimen is attained, increasing the compressive strength.

The other important subject in determining the mechanical properties of rock and concrete materials is under the influence of specimen size on strength characteristics. Many experimental and analytical studies have been undertaken on the effect of specimen volume on the mechanical properties of concrete and rock samples. It is generally known that there is an important reduction in strength with increasing specimen diameter. Moreover, the study of Masoumi et al. [23] indicated that fractal characteristics and surface flaws affect the ascending behavior of the strength relative to specimen size. Also, the laboratory research results of Faramarzi and Rezaee [1] on the effects of sample size on compressive strength showed that compressive strength increases with increasing sample size for a grain size of 12 mm. Darbor et al. [2] maintained by increasing sample size, the possibility of the appearance of micro-cracks and pores in the sample increases. Thus, the structural flaws act as weak points and make the specimen rupture quickly when the sample is placed under loading.

In previous research on cementitious material, there are limited references to studying the effect of anisotropy due to the orientation of discontinuity planes. The present paper systematically investigates the influence of discontinuity orientation, aggregate size, and specimen volume on the compressive strength, tangent modulus of elasticity, overall Young's modulus, modulus anisotropy, and destruction-specific energy. Compared with previous research, the present study is advantageous in that it is based on an extensive and comprehensive experimental dataset obtained from specimens with the different orientations of discontinuity planes, aggregates sizes, and volumes to provide a better understanding of the effects of anisotropy and heterogeneity on the mechanical properties of rock and concrete materials.

2. THE EFFECT OF ANISOTROPY ON MECHANICAL PROPERTIES

Rocks are generally anisotropic due to their physical and mechanical properties. Usually, anisotropic rocks have different physical, mechanical, and hydraulic properties in different directions. The shape of the compressive strength curve and the orientation angle (the angle between the discontinuity and the direction of major principal stress) are the most common representation of the nature of strength anisotropy [24]. The concept of strength anisotropy in rocks, due to the effect of a discontinuity plane, was developed by Jager (1960). The anisotropy curve of uniaxial compressive strength is usually U-shaped, However, the presence of more than one discontinuity changes the shape of the anisotropy curve [25]. In a study conducted by Ramamurthy (1993), the types of anisotropy were determined concerning the orientation angle β, and three types of anisotropy curves were defined: 'U-shaped, shoulder shaped, and wavy shaped [26] (Figure 1).

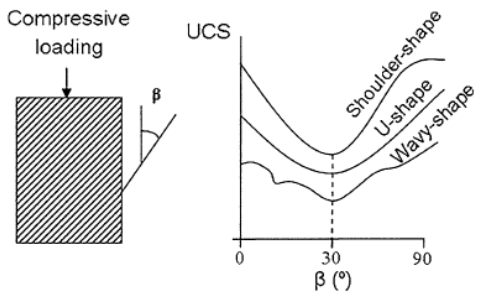


Fig. 1. Variation of the uniaxial compressive strength (UCS) with the orientation of the weakness plane (β) [26].

Usually, a single plane of anisotropy, such as a joint plane or bedding plane (Figure 2, case 1), has a single U-shaped curve with two shoulders, which can be called a shoulder-type anisotropy curve. A set of discontinuities, such as lamination, foliation, or cleavage, have a U- type anisotropy curve without a shoulder (Figure 2, case 2). When two sets of discontinuities intersect each other with an angle of 90^0(Figure 2, case 3), two U-shaped curves are formed by two sets of discontinuities, and the formed curve is W-shaped, with two maxima at $\beta = 0^0$ and $\beta = 90^0$, and two minima will be approximately at $\beta = 30^0$ and $\beta = 60^0$, and a central hump will be approximately at $\beta = 45^0$ [25]. The effect of anisotropy on the modulus of elasticity (E) has also been studied by various researchers. Figure 3 shows the modulus variation with the plane angle (β) in different rocks.

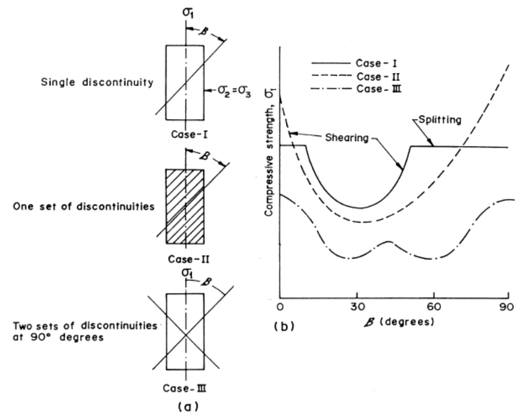


Fig. 2. Typical strength anisotropy curves for samples with single, one set, and two discontinuities [25].

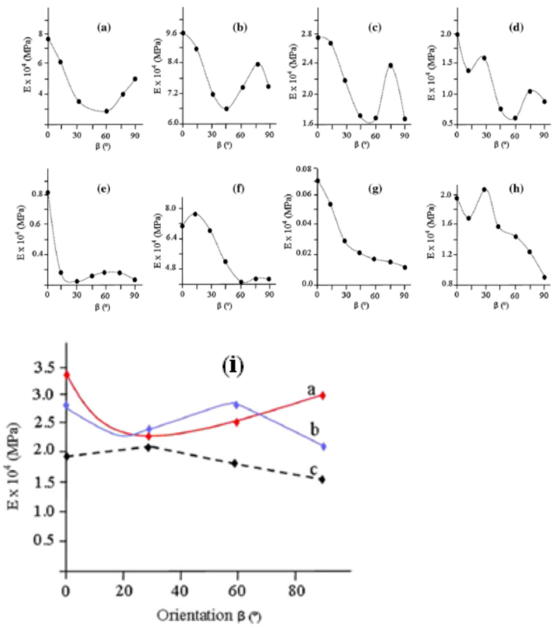


Fig. 3. Variation of modulus with the plane angle (β), a–d: U-shaped, e–h: decreasing order-shaped, (after, Nasseria et al. 2003). a). Hasst schist after Read et al. (1987). b and f). Graywake schist after Pinto (1970). c, d, and h). Shale and silty shale after Kwasniewski and Neuyen (1986). e). Barnsley hard coal after Pomeroy et al. (1971). g). Diatomite after Allirote and Boehler (1970) i). a and b are "U-shaped" and c is "decreased order-shaped" in amphibolite rocks [26].

Research has shown that the uniaxial compressive strength of intact rock decreases with increasing sample size due to the increase of defects in the sample volume and also the increase of anisotropy. However, the change process is dependent on the type of rock, mineralogical composition, porosity, etc. [28-27]. One of the best methods to investigate one parameter, without the influence of other parameters, is the physical modeling of the rock mass using artificial materials such as concrete. The physical modeling of the rock mass with fixed and presupposed characteristics can facilitate the study of various parameters, such as the effect of changes in the discontinuity angle, aggregate size, and sample size [5]. Considering the properties of concrete, it can be easily prepared with pre-designed properties with different combination ratios of sand, water, cement, and particles of different sizes, according to existing standards. Therefore, for the above reasons and the possibility of modeling, concrete can be one of the most suitable materials for the physical modeling of rock mass. In this study, in order to investigate the effect of discontinuity angle, aggregate size, and sample size on mechanical properties and destruction-specific energy, physical modeling has been used.

2.1. The Effect Of Texture On Mechanical Properties

In rock engineering, the selection of equipment and optimum operation depends largely on the quality and quantity of textural and mechanical data available for the rock. Textural characteristics are a significant factor in determining the mechanical behavior of rocks and in predicting the performance of rock cutting and drilling equipment. The principal textural characteristics of rocks are grain size, grain shape, grain orientation, the relative proportion of grains, and matrix material. These features resulted in a texture coefficient represented by a single number for each rock specimen. Rock texture has been defined as "the degree of crystallinity, grain size or granularity and the fabric or geometrical relationship between the constituents of a rock." Grain boundary relationships also play an important role in crack propagation and mechanical performance (particularly in igneous rocks) [29]. Observational and correlated data are strongly supportive of the suggestion that the texture coefficient is a measure of the resistance of the microstructure of a rock to crack propagation, whether it be inter-or intragranular. Texture coefficient and intact rock property relationships are linear to some degree. For example, igneous rocks had high texture coefficients, high strength, and low drillability [30]. The method of a quantitative assessment of rock texture consists of four components:

1- Measurement and analysis of grain circularity, 2- Measurement and analysis of grain elongation, 3- Measurement and quantification of grain orientation, and 4- Weighting results based upon the degree of grain packing. The procedure for analysis can be reduced to the following formula:

$$TC = AW[\left(\frac{N_0}{N_0+N_1}\times\frac{1}{FF_0}\right) + \left(\frac{N_0}{N_0+N_1}\times AR_1 \times AF_1\right)] \quad (1)$$

Where, TC: texture coefficient, AW: grain packing weighting, N_0: number of grains whose aspect ratio is below a pre-set discrimination level, N_1: number of grains whose aspect ratio is above a pre-set discrimination level, FF_0: arithmetic mean of discriminated form-factors, AR_1: arithmetic mean of discriminated aspect ratios and AF_1: angle factor, quantifying grain orientation [30].

3. PHYSICAL MODEL

3.1. Initial Materials And Mixture Composition

3.1.1. Cement

Portland cement which corresponds to ASTM Type I and has been made by the Shahr-e Kord cement factory was used with a 28-day compressive strength of 61 MPa. The mechanical and physical properties of the cement used are given in Table 1.

Table 1. The mechanical and physical properties of cement used in physical modeling

Density (gr/cm^3)	Blaine (cm^2/gr)	Setting time of concrete (min)		UCS (MPa)			
		Initial	Final	2 days	3 days	7 days	28 days
3.15	3.2×10^3	90	170	22	33	47	61

3.1.2. Fine aggregate

The fine aggregate used was from natural river sand with a diameter of 0 to 5 mm, whose fineness modulus was three, and having rounded and smooth particles. Fig. 4 provides the particle size distribution of the fine aggregates.

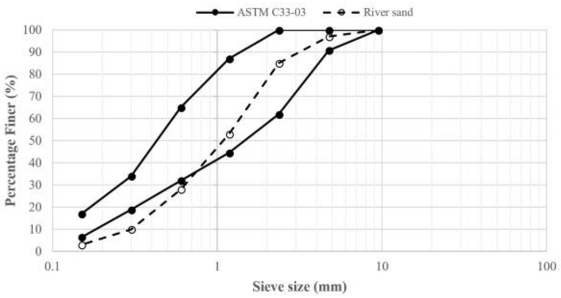
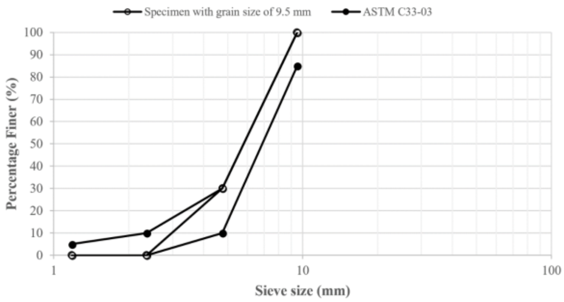
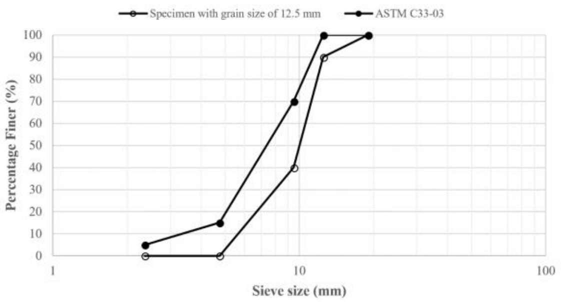


Fig. 4. Particle size distribution of river sand used in cement mortar mix [following the methodology outlined in ASTM C33-03 (ASTM 2003)].

3.1.3. Crushed coarse aggregate

The mineralogy of the coarse aggregates is limestone with maximum sizes of 9.5, 12.5, and 19 mm. Fig. 5 provides the particle size distribution of the Coarse aggregates.





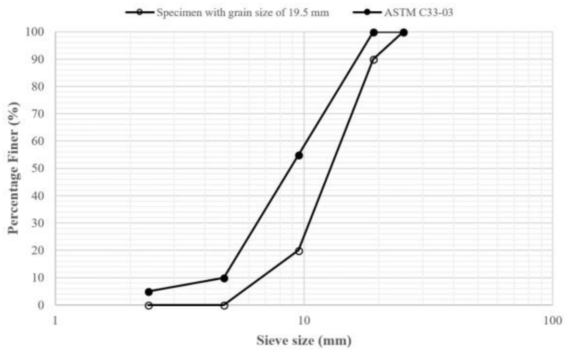


Fig. 5. Grain size distribution of coarse aggregate used in cement mortar mix [following the methodology outlined in ASTM C33-03 (ASTM 2003)] (a) for the 0–9.5 mm coarse aggregates; (b) for the 0–12.5 mm coarse aggregates; (c) for the 0–19 mm coarse aggregates.

3.1.4. Mixture composition

Physical models were prepared using three types of crushed coarse aggregates with a grain size of 9.5, 12.5, and 19 mm, plus fine particles. ACI-211 [31] and ASTM C33 [32] standards were utilized for the mixture design of samples and the required grain sizes, respectively. Initially, the dry materials were thoroughly mixed with the required proportions. Then, water along with the superplasticizer was added, and the concrete was mixed up. The following mix design was used: 525-575 kg of type I Portland cement, water-to-cement ratio of 0.40 (w/c = 0.40), a cement density of 3.15 gr/cm^3, and a Blaine fineness of 3.2× 10^3 cm^2/gr. For each concrete mixture, a slump test was implemented according to ASTM C143–90a. The slump values ranged between 65 and 75 mm. Table 2 illustrates the mixture composition and the characteristics of the coarse and fine aggregates used in the specimens.

Table 2. Composition of the mix utilized for three different grain sizes

Panel number	D_{Max} (mm)	Water/cement ratio	Stone fines (kg/m^3)	River sand (kg/m^3)	Cement (kg/m^3)	Superlubricants (kg/m^3)
1	9.5	0.4	700	790	575	5.75
2	12.5	0.4	900	700	550	5.5
3	19	0.4	900	705	525	5.25

For the preparation of physical models with dimensions of 50 cm × 50 cm × 50 cm and with three different orientations of the discontinuity planes (α) 30°, 45°, and 60° were manufactured a metal mold with the possibility of rotation in different angles where α is the angle between the direction perpendicular to coring/loading direction and the plane of discontinuity. After placing the mold on the desired angle, six various layers with the same spacing were poured into the mold at a time interval of 6 hours (Fig. 6). A vibrator was utilized to compact the concrete, fill the voids, and as well as the workability of concrete specimens. In the following, concrete blocks were cured for 28 days in water at 22°C. In this study, different physical models with three-grain sizes of 0-9.5 mm, 0-12.5 mm, and 0-19 mm and with three orientations of the discontinuity planes of 30°, 45°, and 60° were produced. An overview of the prepared concrete block with a grain size of 0-12.5 mm and orientation of the discontinuity plane of 30° is given in Fig. 7.

Fig. 6. An overview of preparing physical models with 6-hour intervals to create discontinuity planes.

Fig. 7. An overview of concrete block with a discontinuity angle of 30° (Grain size: 0-12.5 mm), α: the angle between the direction perpendicular to coring/loading direction and the plane of discontinuity, S: spacing of discontinuity planes.

3.2. Preparation Of Specimens And Laboratory Tests

Once the specimens were cured for 28 days, a new automatic laboratory drilling machine with bits of 52, 76, and 102 mm in diameter was utilized to make cylindrical cores with a height of 500 mm and three core diameters of 45, 69, and 94 mm. The cores were drilled in two directions perpendicular to the discontinuity plates (Fig. 8). The procedure for determining the discontinuity surfaces on cores drilled from different concrete blocks is shown in Fig. 9. In the following, an extensive program of laboratory studies, including studies of uniaxial compressive strength, tangent modulus of elasticity, overall Young's modulus and destruction-specific energy were conducted.

Fig. 8. An overview of drilling in two directions perpendicular to the discontinuity plate.

Fig. 9. Procedure for determining the discontinuity surfaces on cores drilled from different concrete blocks.

4. EXPERIMENTAL RESULTS AND DISCUSSION

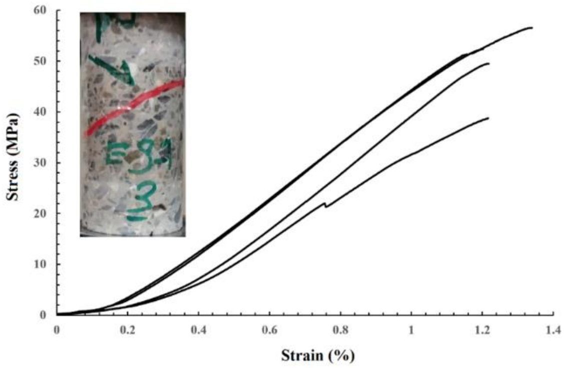
4.1. Effects Of Anisotropy On Strength Parameters

Rock and concrete strengths are a function of their chemical and mineral composition, geometry, characteristics of discontinuities, grain size, grain arrangement, and pore structure, as well as the cement type used. The mechanical properties of rock and concrete specimens can be determined under laboratory conditions using uniaxial or lateral stress tests. The uniaxial compression test is used to determine the uniaxial compressive strength, tangent modulus of elasticity, overall Young's modulus, and Poisson's ratio of rock and concrete materials.

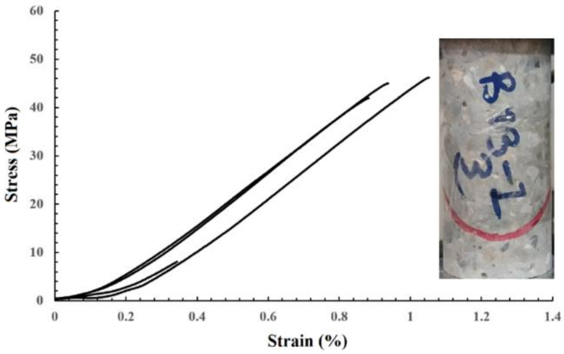
4.1.1. Uniaxial compressive strength

The mechanical properties of the anisotropic concrete blocks depend on the mechanical properties of the individual constituent materials and interfaces. The uniaxial compressive strength (UCS) is one of the most frequently studied properties in rock engineering. For the current study, 124 cylindrical specimens with a length-to-diameter ratio equal to 2 at three different orientations of anisotropy planes (α= 30°, 45°, and 60°) were cored for uniaxial compressive tests according to the recommendation by the International Society of Rock Mechanics (ISRM) [33]. The stress rate was applied within the limits of 0.5–1.0 MPa/s. At a minimum, four specimens from each block and each diameter were subjected to the UCS test, and the average values were recorded as the UCS. The tests were carried out using an electro-hydraulic servo-controlled testing machine. The UCS tests were carried out according to ISRM (1978), and ASTM (1984) suggested methods.

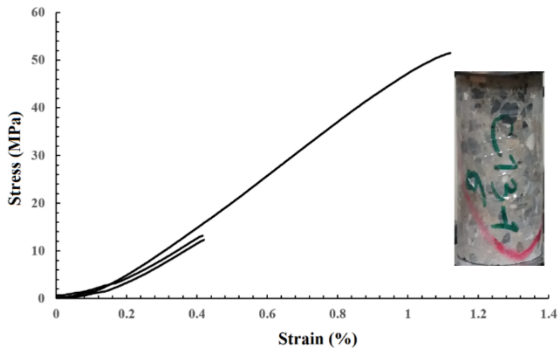
Uniaxial compressive strength tests were conducted on prepared samples, which had a diameter ranging from 45 to 94 mm, grain size of 0-9.5 mm, 0-12.5 mm, and 0-19 mm, and the orientations of the discontinuity planes of 30°, 45°, and 60° and a length-to-diameter ratio of 2. In order to study the behavior of the specimens under uniaxial compressive loading, the stress-strain diagrams were plotted for each specimen. Fig. 10 presents the stress-strain curves for the specimens with the orientations of the discontinuity planes of 30°, 45°, and 60° with a grain size of 0-12.5 mm and a diameter of 45 mm that failed in uniaxial compression tests. Variations exist in compressive strength values among the specimens in the different groups. In specimens with a grain size of 0-12.5 mm, UCS values decrease with increasing α from 30° to 60°. In low α angles, the failure type of most specimens is a normal failure and, with increasing α, changes to shear failure. Also, it can be observed that the area under the stress-strain curve, representing the absorbed energy, decreases with increasing α from 30° to 60°. Results of laboratory tests reveal the high likelihood of a direct relationship between the orientation of the discontinuity plane and grain size with the energy needed to fracture the specimens.



(a)



(b)



(c)

Fig. 10 Stress-strain curves for the specimens with a grain size of 0-12.5 mm and diameter of 45 mm, (a) $\alpha = 30^{\circ}$; (b) $\alpha = 45^{\circ}$; (c) $\alpha = 60^{\circ}$

Average values of UCS for a grain size of 0-12.5 mm in the different orientations of the discontinuity planes and sample sizes are presented graphically in Fig. 11. It was shown that in concrete specimens similar to rock samples studied by Amadei [6], the average uniaxial compressive strength decreases with an increasing orientation of the discontinuity planes from 30° to 60°. For all samples, failure occurred in intact rock at angles of 0° and 90°. However, the failure of most samples was a shear failure for the orientation of the discontinuity planes between 0° and 90°. In other words, the closer we get from 0°

to 60°, the effect of grain size decreases and the effect of discontinuity plates increases, and the closer we get from 60 degrees to 90 degrees, the effect of grain size increases and the effect of discontinuity plates decreases. Also, the average UCS, with a diameter of 69 mm, shows the lowest values, and the diameters of 45 and 94 mm, indicate values close to each other. Additionally, the average UCS in the diameter of 69 mm tends to lower the limits of the uniaxial compressive strength. In this diameter, the failure of most samples was a shear failure.

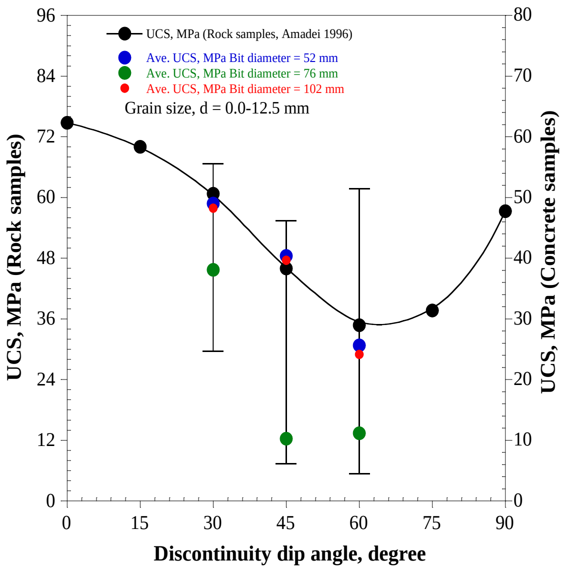


Fig. 11. Comparison of UCS variations in a study conducted by Amadei (1996) and present research concerning the orientation of the discontinuity plane for different diameters, grain size: 0-12.5 mm, (bars indicate the minimum and maximum values of UCS and points indicate average values of UCS).

In grain size of 0-9.5 mm, the results revealed that for all diameters, average UCS decreases with increasing α. Results are illustrated graphically in Fig. 12. In this grain size, similar to the grain size of 0-12.5 mm, the failure of most samples in diameter of 69 mm is a shear failure. This decreasing trend, however, is slower in the case of grain sizes larger than 0-9.5 mm. By increasing the grain size, longer weak paths are provided for crack growth and propagation; this will cause a faster decrease in material strength.

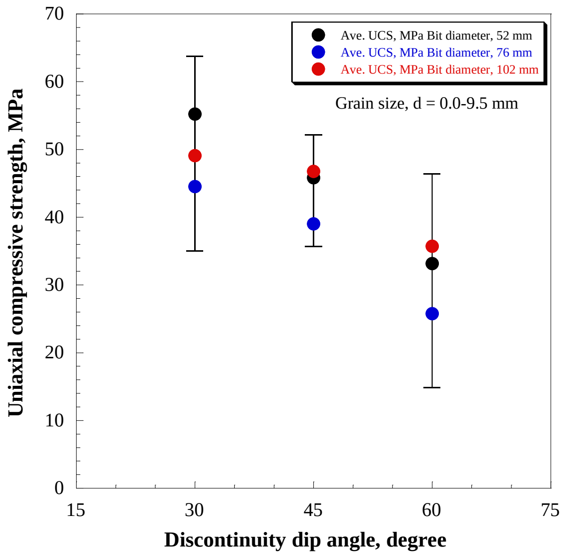


Fig. 12. UCS Variations concerning the orientation of the discontinuity plane in different diameters, grain size: 0-9.5 mm (bars indicate the minimum and maximum values of UCS, and points indicate average values of UCS).

Fig. 13 the depicts values of average UCS in specimens with a grain size of 0-19 mm for three diameters of 45, 69, and 94 mm. The results exhibit that in samples with a diameter of 69 mm has observed an increasing trend of compressive strength from $\alpha = 30°$ to $\alpha = 45°$ and then a decreasing trend from $\alpha = 45°$ to $\alpha = 60°$. With the constant volume and increasing aspect ratio (diameter to sample length), strength and ductility increase. However, similar to the two previous grain sizes, the diameter of 69 mm, observe the lowest compressive strength values. In this diameter, the failure of most samples was a shear failure.

Faramarzi and Rezai [1] considered concrete specimens with four diameters of 56, 68, 72, and 94 mm and three different grain sizes. They concluded that initially, the uniaxial compressive strength ascends from the diameter of 56 to 72 mm, and then UCS declines from 72 to 94 mm in diameter. UCS variations in the present research approve a reverse trend compared to the previous laboratory study. This difference can be due to the discontinuity planes defined in the present study, with increasing specimen volume, the likelihood of increasing microcracks and structural defects within the sample increases. Consequently, these structural defects turn into weak points to facilitate the failure of the specimen under loading. Therefore, samples with a diameter of 69 mm reveal less UCS than specimens with a diameter of 45 mm. The difference in the results of specimens with a diameter of 94 mm may be related to the failure type of these specimens. The failure of most samples with 94 mm in diameter changed to the normal failure compared to the shear failure of specimens with 69 mm in diameter.

Investigating the high and low limits of uniaxial compressive strength in different grain sizes reveals that the maximum uniaxial compressive strength (63.7 MPa) observes in the grain size of 0-9.5 mm, the diameter of 45 mm, and the orientation of the discontinuity plane of 30° and the minimum UCS (4.49 MPa) observes in grain size of 0-12.5 mm, the diameter of 69 mm and the orientation of the discontinuity plane of 60°. Consequently, the maximum uniaxial compressive strength is obtained in finer grain sizes. By increasing the grain size, longer weak paths are provided for crack growth and propagation; this will cause a faster decrease in material strength.

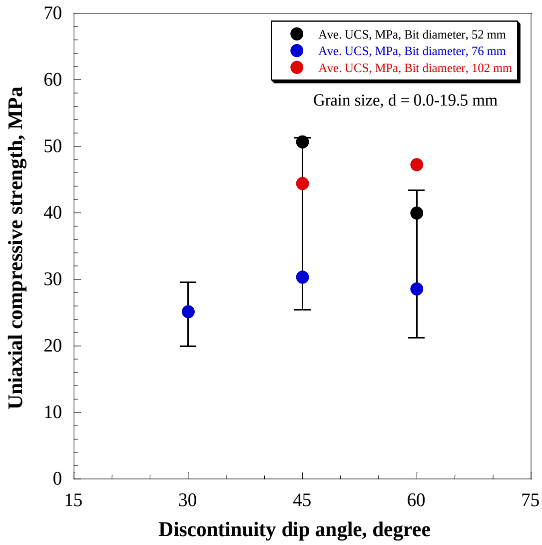


Fig. 13. UCS Variations concerning to the orientation of the discontinuity plane in different diameters, grain size: 0-19 mm (bars indicate the minimum and maximum values of UCS, and points indicate average values of UCS).

4.1.2. Tangent modulus of elasticity

The modulus of elasticity of concrete and rock samples is frequently expressed as a function of uniaxial compressive strength. From the stress-strain diagrams, the modulus of elasticity values was estimated by referring to the tangent modulus measured at 50 % of the uniaxial compressive strength. Fig. 14 shows the experimental results of the modulus of elasticity and modulus anisotropy as a function of the orientation of the discontinuity plane in diameter of 45 mm and grain size of 0-9.5 mm. With increasing the angle of the discontinuity plane from 30° to 60°, the modulus of elasticity in the direction I (E_I) decreases. However, it increases in direction II (E_{II}). Also, the modulus anisotropy (E_I / E_{II}) decreases by increasing the angle of the discontinuity plane from 30° to 60°.

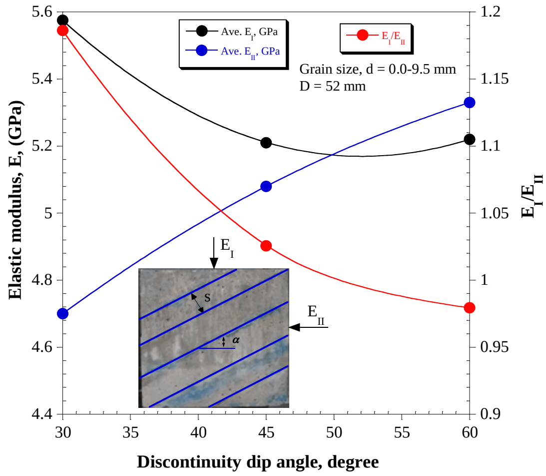


Fig. 14. The influence of anisotropy on the tangent modulus of elasticity and modulus anisotropy, sample diameter: 45 mm, and grain size: 0-9.5 mm.

Results of studies conducted on all laboratory samples revealed that in the diameter of 45 mm, the highest average E (5.59 GPa) observed in the grain size of 0-12.5 mm and the orientation of the discontinuity plane of 45° and the lowest average E (4.65 GPa) obtains in the grain size of 0-12.5 mm and the orientation of the discontinuity plane of 60°. In the diameter of 69 mm, the highest average E (5.24 GPa) observes in the grain size of 0-9.5 mm and the orientation of the discontinuity plane of 30°, and the lowest average E (2.43 GPa) obtains in the grain size of 0-12.5 mm and the orientation of the discontinuity plane of 45°. Also, in specimens with a diameter of 94 mm, the highest average E (5.75 GPa) observes in the grain size of 0-9.5 mm and the orientation of the discontinuity plane of 60°, and the lowest average E (4.45 GPa) obtains in the grain size of 0-19 mm and the orientation of the discontinuity plane of 60°. Consequently, in specimens with diameters of 69 and 94 mm, the highest values of tangent modulus of elasticity are obtained in finer grain sizes because by increasing the grain size, longer weak paths are provided for crack growth and propagation, this will cause faster decrease in material tangent modulus of elasticity.

4.2. Destruction-Specific Energy Of Anisotropic Specimen

The integral of the envelope curve of stress-strain to the peak point of strength is defined as destruction-spe

cific energy (SE_{des}). Destruction-specific energy is derived from the following equation:

$$SE_{des} = \int \sigma \, d\varepsilon \tag{2}$$

Where SE_{des} is the destruction-specific energy (KJ/m3); σ is the stress (MPa), and ε is the strain [34]. The value of the maximum strain (ε_{max}) utilized for determining SE_{des} is the strain value, which is directly connected with the failure, to develop a new surface in the specimen. The SE_{des} is a significant mechanical property for the cutability investigation. Fig. 15 shows the effect of specimen diameter on destruction-specific energy for orientation of the discontinuity planes of 30°, 45°, and 60° and grain sizes of 0-9.5 mm and 0-12.5 mm. Similar to the changes in UCS and E values, average SE_{des} is initially reduced from 45 to 69 mm in diameter and then increases from 69 to 94 mm in diameter. A comparison of SE_{des} values in samples with different angles shows that with increasing the orientation of the discontinuity plane, the destruction-specific energy decreases.

For most samples, the closer we get from 0° to 60°, the effect of grain size decreases and the effect of discontinuity plates increases, and the closer we get from 60 degrees to 90 degrees, the effect of grain size increases and the effect of discontinuity plates decreases.

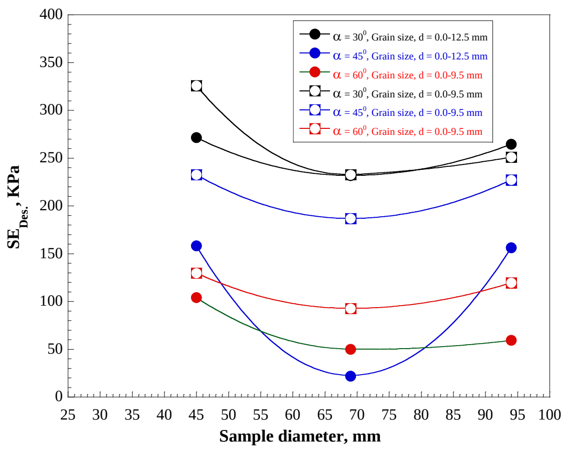


Fig. 15. The influence of specimen size on destruction-specific energy, orientations of the discontinuity planes: 30°, 45°, and 60° and grain sizes: 0-9.5 mm and 0-12.5 mm.

6. CONCLUSIONS

The research study set out to identify the strength properties of concrete specimens utilized based on variations in the orientation of the discontinuity plane, grain size, and sample diameter. Core specimens using an automatic laboratory drilling machine were taken from concrete blocks at three different diameters (45, 69, and 94 mm). Then, comprehensive laboratory tests were performed to investigate the influence of the orientation of the discontinuity plane, grain size, and specimen size on uniaxial compressive strength, behavior curves, tangent modulus of elasticity, overall Young's modulus, modulus anisotropy, and destruction-specific energy. It can be summarized from the present research that the mechanical properties of concrete specimens display different values concerning anisotropy. Based on the experimental results of the present research, the following conclusions can be drawn:

1. Anisotropy has a significant influence on the compressive strength and elastic modulus of concrete samples. The results of uniaxial tests on concrete specimens in grain sizes of 0-9.5 mm and 0-12.5 mm have been shown to decrease when increasing the orientation of the discontinuity plane. With increasing the orientation of the discontinuity plane from 30° to 60°, up to 42% and 71% of compressive strength reduction were observed within the three diameters investigated for samples with grain sizes of 0-9.5 mm and 0-12.5 mm, respectively. In low angles of the discontinuity plane, the failure type of most specimens is a normal failure but with increasing angle of the discontinuity plane changes to shear failure. Also, the closer we get from 0° to 60°, the effect of grain size decreases and the effect of discontinuity plates increases, and the closer we get from 60 degrees to 90 degrees, the effect of grain size increases, and the effect of discontinuity plates decreases.

2. From the elastic deformation test, values of tangent modulus of elasticity of concrete specimens in the direction I with increasing the orientation of the discontinuity plane from $\alpha = 30°$ to $\alpha = 60°$ show a descending trend, while the value of tangent modulus of elasticity reveals an ascending trend in direction II. These variations confirm the effect of anisotropy on the elastic deformation of concrete samples.

3. The results revealed that the mechanical properties of concrete samples are strongly linked to the aggregate parameters of the concrete mixture. An increase in grain size from 0-9.5mm to 0-19mm clearly decreases the compressive strength, tangent modulus of elasticity, and overall Young's modulus. It was observed that increasing grain size rises heterogeneities that affect UCS, E, and E_s. Also, by increasing the grain size, longer weak paths are provided for crack growth and propagation; this will cause a faster decrease in material UCS, E, and E_s.

4. Another aspect of the present study involves an attempt to consider the effect of volumes used in measuring compressive strength and elastic constants of concrete specimens. The current results on the influences of specimen size on uniaxial compressive strength show that the values of compressive strength, elastic modulus,

and destruction-specific energy with increasing sample size from 45 to 69 mm in diameter decreased for different grain sizes while increasing specimen size from 69 to 94 mm in diameter led to significant rises in the values of elasticity modulus and compressive strength of cementitious material. With increasing specimen volume, the likelihood of increasing microcracks and structural defects within the sample increases. Consequently, these structural defects turn into weak points to facilitate the failure of the specimen under loading. Therefore, samples with a diameter of 69 mm reveal less UCS than specimens with a diameter of 45 mm. The difference in the results of specimens with a diameter of 94 mm may be related to the failure type of these specimens. The Failure of most samples with 94 mm in diameter changed to normal failure compared to the shear failure of specimens with 69 mm in diameter.

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