DESIGN, FABRICATION AND EVALUATION OF DIGITAL TILT TEST DEVICE

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ABSTRACT

Due to the high and fluctuating exchange rate, obtaining devices and equipment for practical demonstration of theoretical contents of engineering and applied science courses in developing countries is becoming a herculean task. To sustain the practical aspect of these courses, some of the devices have to be locally manufactured. In this study, a digital tilt test device for determining the basic friction angle and joint roughness coefficient (JRC) of rock samples was designed and fabricated using majorly local materials. Comparing the device's results with those obtained from the Profilometer, there was a satisfactory correlation between the two results. The device is much cheaper to manufacture locally than the imported onesTherefore, it is recommended that the device be used for estimating the friction angle and JRC of rock samples. Similar devices with simple mechanisms should be manufactured locally in higher institutions to reduce dependency on foreign devices, which are expensive.

Keywords: Basic friction angle, JRC, Tilt test device,

1. Introduction

Practical and experimental works are essential components of science and engineering education, especially in higher institutions where the theoretical framework ofthe course content has to be practically demonstrated and applied to real-life cases. One of the obstacles to achieving the practical demonstration is the non-availability of the required tools and devices, which in most cases are very expensive to acquire by some higher institutions in the developing countries due to high and fluctuating exchange rates. However, the institutions could look inward to locally design and fabricate some of this equipment, and in some cases, the mechanism of the device may not be complex. One of such devices isa tilt test device.The device is used, in the laboratory, to determine the basic friction angle of different rock samples.

Basic friction angle is one of the essential parameters for estimating the shear strength of rock discontinuities in the stability analysis of slope and underground excavations (Alejano*et al.,* 2012). Aside from the tilt test, there are other methods for determining the friction angle of rock, such as the direct shear test. However, the tilt test is a much less expensive, simple and relatively fast method to calculate the friction angle of rock samples and the shear strength parameters of the rock discontinuities(Zhang *et al.,* 2018). Therefore, the tilt test device is often used to determine the basic friction angle of the rock joint.

Barton and Choubey designed a simple tilt test device in 1977 to determine the friction angle. After that, many research institutions have designed and fabricated the device with some modifications to suit the purposes of their experiment. For instance, Hacettepe University in Turkey designed a tilt test device, which is hand-operated, while the one designed by the University of Vigo in Spain is motorised and has a regulation system that controls the tilt velocity (Alejano*et al.,* 2017). Many companies specialising in testing equipment have manufactured tilt test devices for commercial purposes, but the cost is relatively high for institutions in developing countries. Hence, as done by many institutions in other countries, producing the device locally will reduce the cost and cater for the specific interest. In this study, the tilt test device was designed and fabricated. The performance of the device was evaluated by using the JRC results of rock samples obtained from the device and compared with the JRC results obtained from using Barton's Profilometer on the same rock samples. The results from the device show a good agreement with those of the Profilometer, which indicates that the device can be reliably used for the tilt test.

2. Design and Fabrication of the Major parts of the Digital Tilt Test Device

The computer Aided Design (CAD) model of the digital tilt test device was developed using SolidWorks CAD application software, as shown in Figures 1 and 2. The parts of the device are; the stands with slipping supporting plate, slipping base plate, sample stopper, guide, sample holder, sample support, screw frame, adjustment screw, lock screw and digital angle inclinometer.

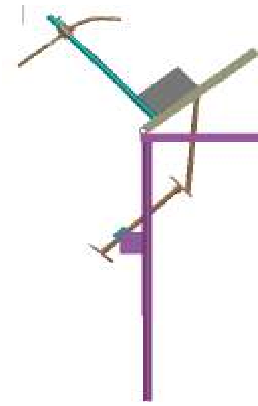
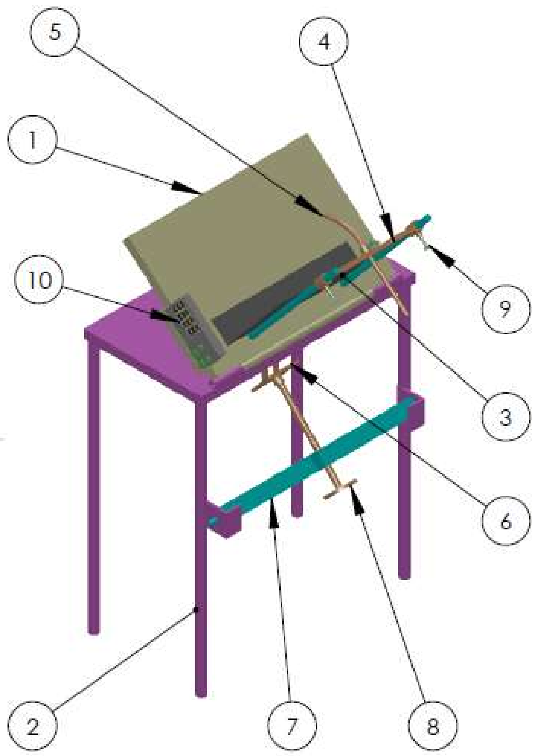


Figure 1: Side view of the Digital Tilt Test Device



ITEM NO.	PART NUMBER	QTY.
1	SLIDING BASE PLATE	1
2	STANDS WITH SLIDING SUPPORTING PLATE	1
3	SAMPLE STOPPER	1
4	GUIDE	1
5	SAMPLE HOLDER	1
6	ADJUSTMENT SCREW-BASE PLATE LINK	1
7	SCREW FRAME	1
8	ADJUSTMENT SCREW	1
9	LOCK SCREW	3
10	DIGITAL ANGLE INCLINIMETER	1

Figure 2: Block diagram of the Digital Tilt Test Device

2.1. Operation ofDigital Tilt Test Device

An adjustment screw regulates the tilting angle of the rock sample. The screw frame holds the adjustment screw. The digital angle inclinometer, which is attached to the inclinometer base plate, measures the change in the angle of the inclined plate when the adjustment screw is turned. The base plate supports the whole device and ensures rigidity. The slipping base plate, which is on top of the base plate, holds rock samples and aids in slipping when the adjustment screw is turned. The sample stopper prevents the rock sample from falling off the slipping base plate, while the hinge ensures the movement of the slipping base plate. The angle iron supports the device at each side of the base plate and holds the inclinometer firmly to the inclined plate. The device is supported on four stands, and different parts of the device are fastened together with bolts and nuts. All the materials used for the design of the device are locally available except the digital angle inclinometer, which was obtained abroad. The materials are durable and light in weight, such that the device will be moveable.

2.2. Design Analysis of major parts of the Digital Tilt Test Devise

The Digital Tilt Test Devise was designed to have a capacity to carry a maximum load (rock samples) of 10kg (98.1N). Based on this capacity, the other parts of the device are designed as discussed below:

2.2.1 The Stands with Slipping Supporting Plate

Thereare four stands, which carry the slipping base plate; they are made of steel pipe (Figure 3). The height of thepipe is 600mm, which is within the range of a standard height for a workshop table (Gaughran, 2004). The four stands are designed to carry a maximum load of 12kg (10kg for the rock samples and 2kg for the slippingbase plate, slipping supporting plate and other parts).

The slipping supporting plate of 490 mm by 270 mm galvanised steel is welded with the stands. Figure 4 shows the von Mises stress distribution pattern on the parts with a maximum load of 12 Kg (117.72N) as obtained from the Finite Element Analysis (FEA) using the hinged portion for the point of load application. It can also be seen that the major area of the element has the minimum (safe) stress of $1.852 \times 10^{-1}\ N/m^2$ out of yield strength of $2.039 \times 10^{8} N/m^2$of the galvanised material and hence suitable for the device.

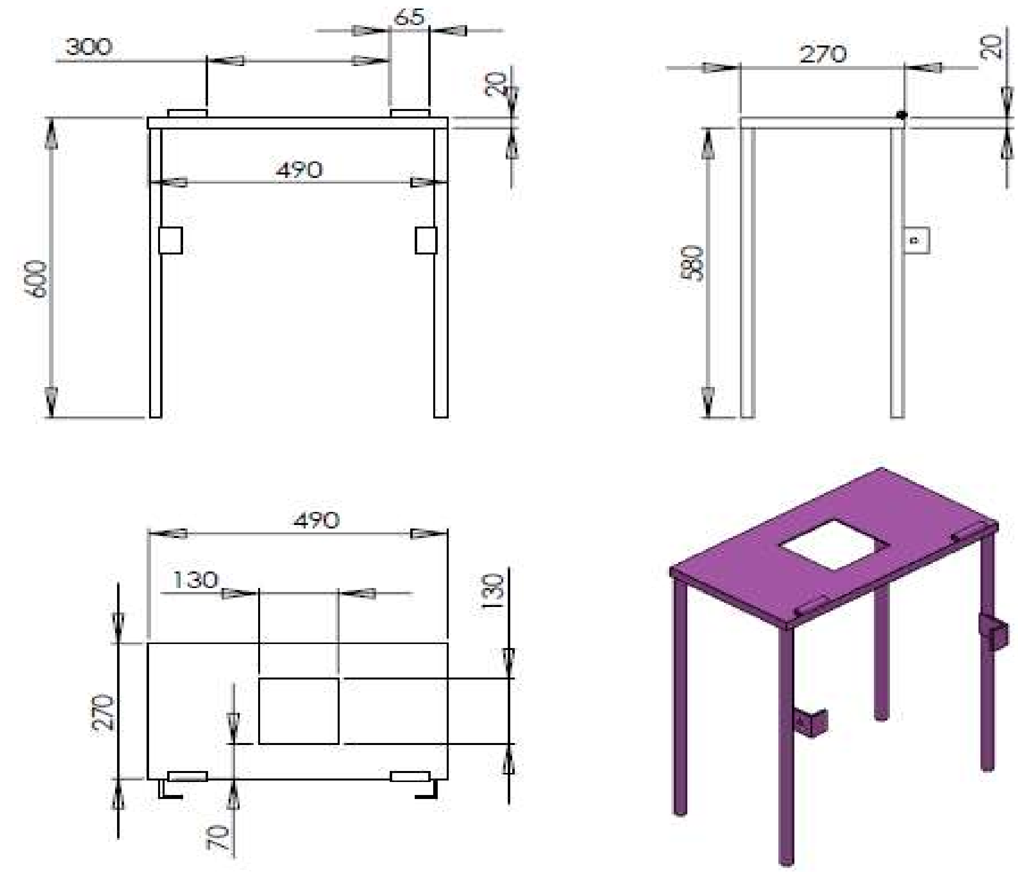


Figure 3: The Digital Tilt Test Device' stands with a Supporting plate

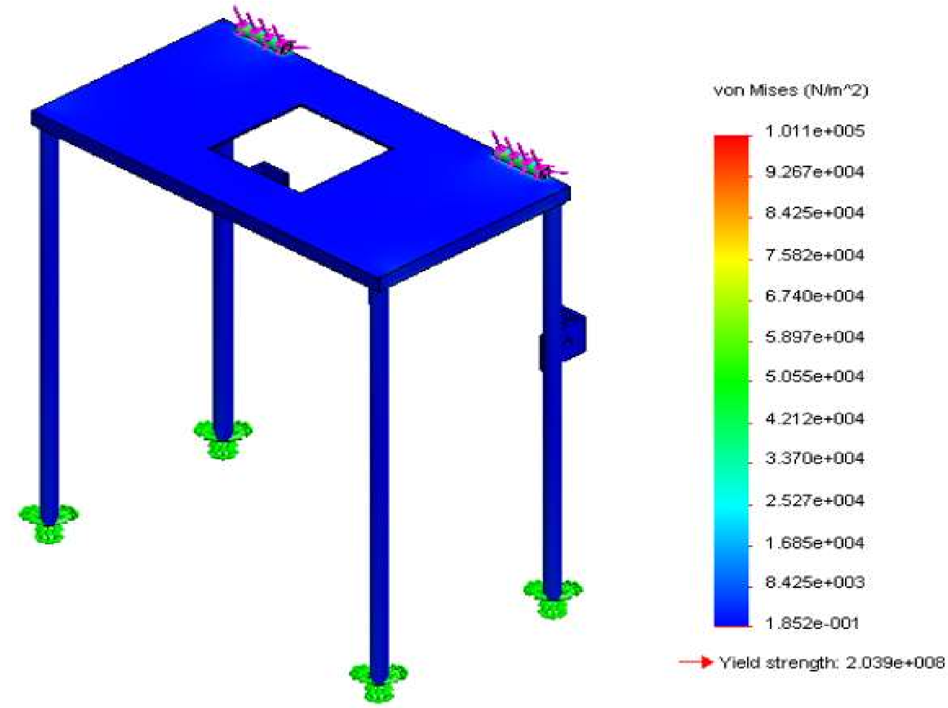


Figure 4: von Mises Stress Distribution of Device's Stands with Supporting plate

2.1.1 SlippingBase Plate

The slippingbase plate shown in Figure 5isa rectangular flat plate made of mild steel. Its dimension is 410mm × 270mm. Its thickness was determined using Equation 1 (Khurmi and Gupta, 2010), assuming that the platecarries a uniformly distributed load.

$$t = a \times b\left(\sqrt{\frac{P}{\sigma_t(a^2+b^2)}}\right) \quad (1)$$

where t is the thickness of the plate (mm), a is the length of the plate (mm), b is the width of the plate, P is the load on the plate (N), σ_t is the allowable design stress, and k is a constant that depends on the material of the plate and the method of holding the edges of the plate. In this situation, k is 0.49 (Khurmi and Gupta, 2010).

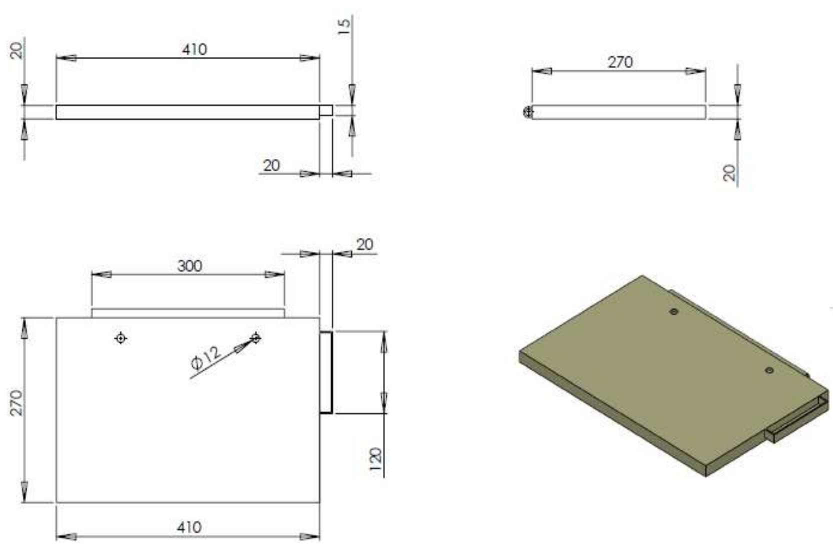


Figure5: Diagram of the Digital Tilt Test Device's Slippingbase plate

2.2.2 Adjustment Screw

Theadjustment screw, shown in Figure 6, transforms rotary motion into linear motion by raising the slipping supporting plate.The thread forms ofthe adjustment screw are square thread, though challenging to cut but more efficient than angular types.The minor diameter of the screw was determined using the equation for the screw under direct compression stress, Equation 2 (Budynas, 2008) and the corresponding nominal diameter and the pitch were found in the Table of Basic Dimensions of ISO Metric Screw Threads (Juvinall andMarshek, 2017).

$$\sigma_a = \frac{4F}{\pi d_r^2} \quad (2)$$

where $\sigma_a$is the allowable stress of the material used for the screw (N-mm^{-2}), F is the load carried by the screw (N), and d_r is the minor root diameter (mm^2).

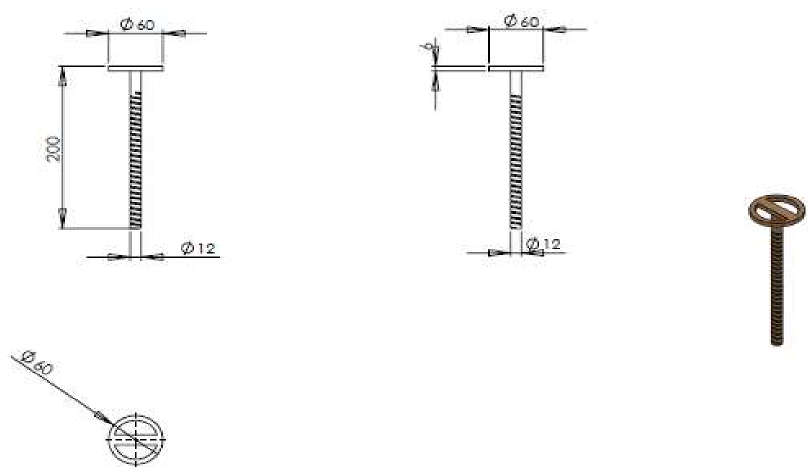


Figure6: Diagram of the Digital Tilt Test Device's Adjustment Screw

2.2.3 Adjustment Screw-Base Plate Link

The adjustment screw-base plate link, as shown in Figure 7, is a mild steel material welded to the slipping base plate, serves as a support for the sample to be rightly held, and transfers the rotary motion of the adjustment screw to the curvilinear (angular) motion of the slipping base plate. Figure 8 shows the von Mises stress distribution FEA of the linking element by subjecting it to a maximum load of 12 kg (117.72 N). From Figure 8, it can be seen that the stress distribution pattern is much around the curved steel rods, which is due to the angle of tilt for the transfer of the load. However, the analysis of the element is upheld due to the selected thickness of the rods and hencethe element canwithstand the load.

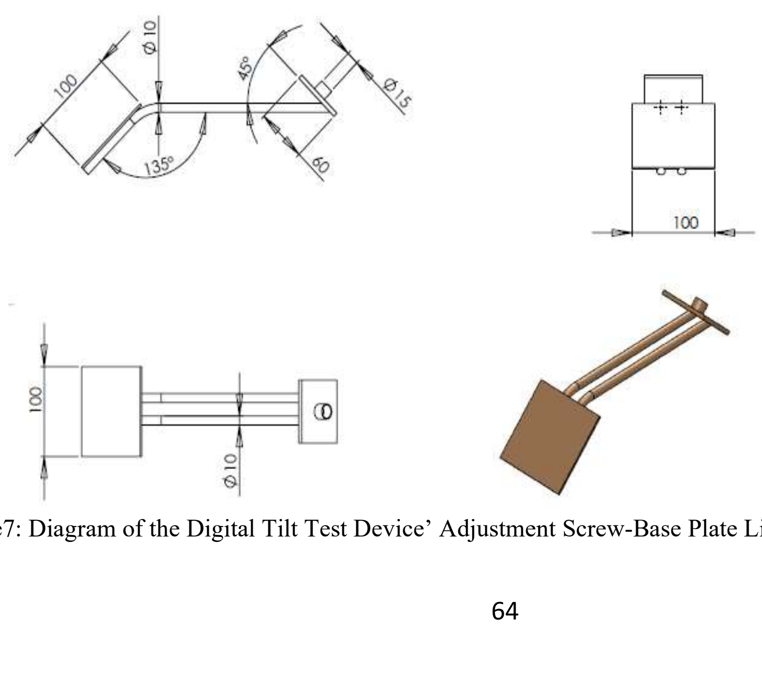


Figure7: Diagram of the Digital Tilt Test Device' Adjustment Screw-Base Plate Link

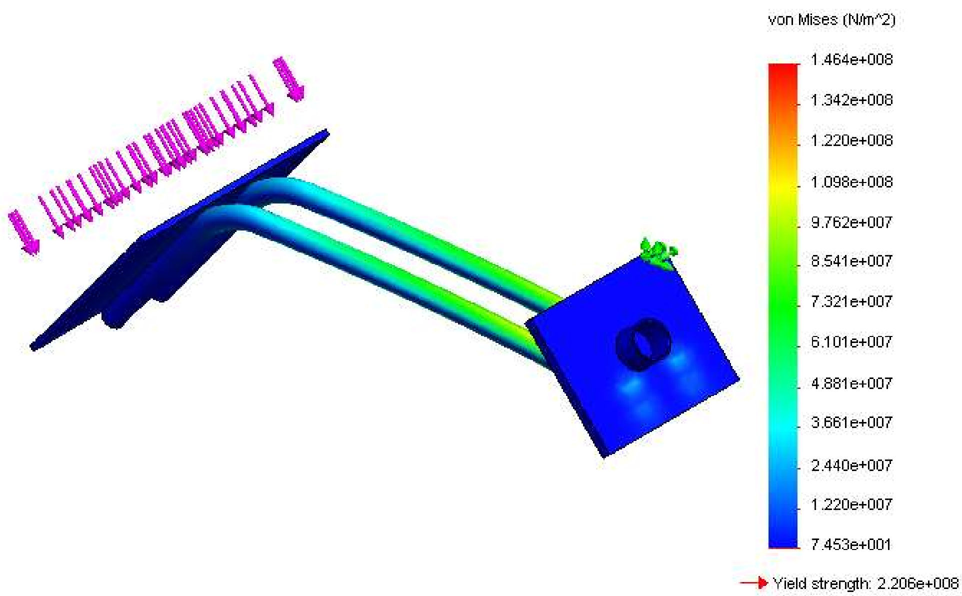


Figure 8:von Mises Stress Distribution of Device's Base Plate link

2.3.

2.4. Fabrication of Digital Tilt Test Device

The fabrication of the device was carried out at the workshop of the Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria. The base plate was cut into a rectangle-shaped from galvanisedsteel metal sheet with a dimension of 490 mm by 270 mm and was supported at the edge with a square steel pipe to ensure rigidity and proper support. The base plate was attached to a circular steel pipe of length 600 mm using arc welding at each edge of the rectangle. Four circular pipes were attached to the base plate for creating the stands, clearance and support for the apparatus. One side of the two hinges was attached to one side of the rectangular breadth of the base plate at the edge and on the top using arc welding. Another rectangular galvanisedsteel metal sheet with a dimension of 410 mm by 270 mm, which is smaller than the dimension of the base plate, was supported at the edge of the plate using a square pipe and angle iron at the centre. The base plate was slightly welded together to avoid bulging of the stainless material to make the other movable slipping plate. The movable slipping plate was attached to the other side of the two hinges to hold the fixed based plate at the bottom and the movable slipping plate at the top. A square steel pipe was welded on the other side of the rectangular breadth of the base plate on the top to level the movable plate on the fixed base plate. At thecentre of the rectangular plate, the other side of the hinge was attached using arc welding. A thick plate of 220 mm by 140 mm was attached to another side of the hinge below the fixed based plate to make a movable plate at the bottom of the fixed plate. The movable top plate was connected to the movable down plate with a straight inclined rod of 270mm length, welded to hold them apart. A thick flat plate waswelded on the circular steel pipe below the fixed based plate, at the middle of the circular steel pipe's length below the welded hinge's location. A screw frame of length 270 mm in the form of angle iron with a nut attached at the centre as an adjustment screw is then bolted to the thick flat plate that makes it movable radially. The adjustment screw of the length 330mm was screwed into the screw frame then the bearing was attached to the adjustment screw through welding. The end of the bearing was attached perpendicularly to the plate using welding so that when the adjustment screw has been turned forward, the movable base plate moves upward. The sample holder was attached to the top of the movable slipping plate to hold the sample after slipping using welding. The device was painted to prevent rusting and enhance its aesthetic value.

3. Device Performance Evaluation

The performance of the designed and fabricated tilt test device was evaluated by using the device to back-estimate the Joint Roughness Coefficient (JRC) for some selected rock samples. The obtained results of the JRC were compared with the JRC values of the rock samples estimated by using a Profilometer. According to Barton *et al*. (1985), the JRC can be estimated for the rock samples using Equation 3

$$JRC = \frac{\alpha - \varphi}{log\left(^{JCS}/_{\sigma_n}\right)} \quad (3)$$

whereα is the tilt angle when slipping occurs along rough surfaces of a pair of rock samples, σ_n is the normal stress applied to the joint, JCS is the compressive strength of the joint surface, andφ is the residual friction angle, which can be estimated according to Barton &Choubey (1977)using Equation 4:

$$\varphi = (\theta - 20°) + 20\frac{r}{R} \quad (4)$$

where θ is the basic friction angle,r is the Schmidt hammer rebound number measured for a weathered and wet rock joint, such as those typically found in the field and R is the Schmidt hammer rebound number obtained for an unweathered surface of the same rock.

In the following sections determination of the parameters for estimating the JRC using Equations 3 and 4 is discussed.

3.1.1. Determination of slipping angle (α) and basic friction angle (θ)

The basic difference between α and θ is the nature of the rock sample surface along which the slipping occurs. Ten granite samples with natural joint surfaces were obtained from a quarry. Each sample was cut into a block sample, and the weight was determined. The rough surfaces of the rock samples were not tampered with to maintain the in-situ condition and get the accurate slipping/tilt angle for the rough surfaces. Two roughed surfaces are combined to form one pair and five pair samples (A1, A2, A3, A4 and A5) were obtained from the ten samples. Each of the pair was placed on the tilt test device to get the relative slipping angle of the two surfaces in contact. The tilt device was adjusted until the sample on the top began to slide under its weight. The tilt test was performed for the five pairs, and the slipping angles for the rough surfaces (α) were recorded, as shown in Figure 9(a). For the smooth surface, ten block samples of the granite rock were prepared, and the weight of each sample was determined.The surfaces of the sample were cleaned to remove any dust or particles. A sample was placed horizontally over the other to make five pairs and named B1, B2, B3, B4 and B5. Each pair of the samples was placed on the tilt test device. The device was adjusted until the upper sample slipped over the sample below along the smooth surface. The slipping angle, which is the basic friction angle (θ), was recorded; an example is shown in Figure 9 (b).

Figure 9: Tilt angle for: (a) sample with rough surfaces (b) sample with a smooth surface

3.1.2. Determination of the normal stress (σ_n) and Joint Wall Compressive Strength (JCS)

The normal stress, which was applied on the rough surface by the weight of the upper sample when it began to slip, was estimated using Equation 5.

$$\sigma_n = \frac{Wcos\alpha}{A} \quad (5)$$

where W is the weight of the upper rock sample,A the area of its contact surface and α is the slipping angle.

The joint wall compressive strength (JCS) was determined from the rebound test using a Schmidt hammer. The Schmidt hammer was applied vertically on the smooth and rough surfaces of the samples to avoid using any correction factor when the application is inclined and this was repeated 15 times for both the smooth and rough surfaces and the results, which are Reynolds numbers were denoted as R and r, respectively. Top ten R and r were selected and their mean calculated.The mean Reynolds number of the sample with a rough surfaceis equivalent to the joint wall compressive strength (JCS) of the rock sample (Barton, 2016).Having determined the mean$R$ and r from the rebound test and the basic friction angle (θ) using the tilt test device, the residual friction angle (φ) was estimated using Equation 4.

3.1.3. Determination of joint roughness coefficient (JRC) using Profilometer

The Profilometer was used on the sample to get the roughness profile of the weathered sample (i.e. samples with rough surfaces). The Profilometer was placed directly on the weathered surface. Slight pressure is exacted on the Profilometer to get the profile reflected on the profiler combs, as shown in Figure 10 (a). The profile was compared with the standard profile for joint roughness coefficient presented by Barton and Choubey (1977) to get the corresponding JRC. Figure 10 (b) shows the Profilometer and the standard profile for JRC.

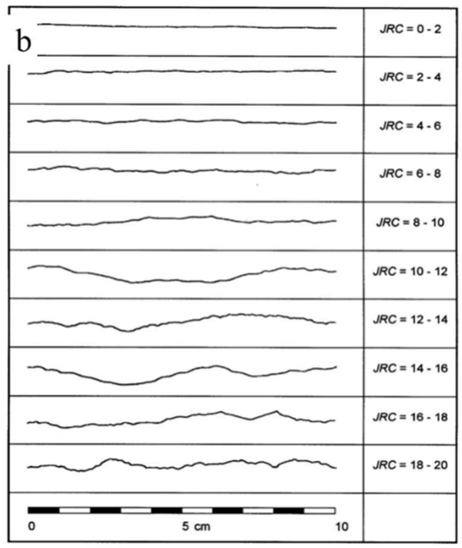


Figure 10: (a) Profilometer (b) Standard Profile for JRC

4. Results and Discussions

The tilt test device for the determination of basic friction angle and JRC of rock samples was designed using both conventional method of machine design and Finite Element Analysis (FEA) to determine the allowable stress and stress distribution pattern on the major parts of the devise with a maximum load of 117.72 N the results shown that the allowable stress of each of these parts is below its corresponding yield strength. The components of the device were locally available except for the digital inclinometer that was obtained from China. The total cost of fabricating the device is approximately Fifty thousand Naira (approximately 120 USD), which makes it much cheaper when compared to the cost of obtaining a similar device abroad. An Imported analogue tilt test device costs approximately 850 USD in the UK. (www.controls-group.com). Figure 11 shows the developed digital tilt test devise.

Figure 11: Developed Digital Tilt Test Device

The developed digital tilt test device (DTTD) was used to determine the slipping angle (α) for each of the rock samples with weathered rough surfaces (A1-A5) and for the basic friction angle (θ) for the samples with un-weathered smooth surfaces (B1 – B5). These results are shown in Table 1. The table further shows the values of JRC for each of the samples A1 to A5 which were determined using Equation 4 based on the slipping angle (α) and the basic friction angle (θ) and also the corresponding JRC range for each of the samples using profilometer. It can be observed that the slipping angles (α) are higher than the corresponding basic friction angles (θ). This is due to the rough surfaces of the samples which increase the friction between the surfaces. Hence the increase in the angle at which the samples slipped.

Comparing the values of JRC obtained from the developed DTTD with the standard JRC for each of the samples, it can be observed (from Table 1) that the results of the JRC obtained from using the device were within the range of the results obtained by using the Profilometer for the samples except for the sample A5. This shows that the developed DTTD is reliable and efficient for determining the JRC of rock samples

Table 1: Results of Slipping and Basic Friction Angle obtained from the Developed Tilt Test Device and the calculated Joint Rough Coefficient and Joint Rough Coefficient from Profilometer

Rock Samples (weathered rough surfaces)	Slipping angle (α) (°)	JRC		Rock Samples (un-weathered smooth surface)	Basic friction angle (θ) (°)
		Using Equation 4	Using The Profilometer*		
A1	27.30	3	2 – 4	B1	24.70
A2	57.20	10	8 – 10	B2	30.70
A3	47.20	7	6 – 8	B3	28.80
A4	37.10	5	4 – 6	B4	27.00
A5	48.50	8	10 – 12	B5	28.90

* Source: Barton and Choubey (1977)

5. Conclusions

A tilt test device, which is used for determining friction angle and *JRC* of rock samples, was designed and fabricated using local material. The performance of the device was evaluated by comparing the results obtained when the device was used to back-estimate the JRC of some rock samples. The JRC results obtained from the device were compared with those obtained using the Profilometer. They show good correlation, indicating that the apparatus is efficient and can be used successfully to estimate basic friction angle and JRC of rock samples. The cost of manufacturing the device from the locally available material is cheaper when compared to the cost of buying the device abroad. Similar devices for practical demonstration of the theoretical content of engineering and applied science courses should be locally manufactured rather than depending on the importation of the devices. Students should be involved in the manufacturing process of these devices as their final year degree projects. This will enhance their competency and mindset to proffer locally-oriented solutions to some of the developing nations' problems.

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