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Determination of static friction coefficient of a material using clamp method

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ABSTRACT The increasing importance of climbing mechanisms in construction and maintenance work arises from the necessity of safe and efficient access to hard-to-reach areas. However, there is still limited research on the clamping force of various materials required for developing climbing mechanisms. To address this, further research is needed to investigate the clamping force and static coefficient of friction of different materials on-site. The main objective of this research is to explore the relationship between clamping force, static coefficient of friction, and applied gravitational force while investigating the static coefficient of friction of different materials on a pole. A clamping device has been proposed for evaluating the static coefficient of friction for different plastics and rubbers. A test method using clamping force as independent variable has been discussed for using such apparatus. The experimental results revealed that rubber materials generally exhibit higher static coefficient of friction than plastic materials. Its findings can serve as a valuable foundation for future research and the development of climbing mechanisms to enhance their usage in construction and maintenance work.

KEYWORDS: Coefficient of friction; Static friction; Frictional force, Clamping; Climbing mechanism.

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INTRODUCTION

Construction industry is a hazardous and complex industry that requires involvement of different sets of tasks, materials, and machineries at harsh and risky environment (Jaafar *et al*., 2017). Safety is a top priority in any construction project, but accidents can still occur due to various reasons. A study conducted on fatal accidents in Malaysian' construction industry between 2013 and 2018 by the Department Safety and Health (DOSH) Malaysia found that fatalities due to falling from heights and stuck by falling object were the most common types of causes, accounting for 43% and 21% of the cases, respectively (Abdul Halim *et al*., 2020). These fatalities involve workers who performed tasks at elevated locations, such as on rooftops, scaffolding, ladders, or elevated platforms, which are particularly vulnerable to falling. Even a fall from a relatively low height can cause serious injuries. Therefore, it is essential that workers who perform tasks at height are provided with proper safety equipment and trained in safe work practices, or to be replaced by robots such as pole-climbing robots for routine tasks.

To develop a reliable climbing robot, or to ensure proper grasp of objects at height from falling, the static friction between objects to ensure stationary condition should be studied. The static coefficient of friction is a measurement of the amount of frictional force that must be overcome to initiate motion between two surfaces in contact when they are at rest with respect to each other. Coefficient of friction between different materials can be determined via laboratory experiments apparatus such as inclined plane coefficient of friction tester, and ASTM D1894 coefficient of friction tester. Rodriguez-Arias (2019) designed and created a device to measure the coefficient of static friction. The device consists of several components, including an Arduino, a screen, a platform, a linear potentiometer, an infrared motion sensor, and a variable speed gearmotor. These existing test methodologies to determine coefficient of static friction rely on sliding motion between two flat surfaces.

However, specific methodology or fixtures were developed when there is specific need, particularly to perform in-situ measurement on large specimen or during an operation such as pin-on-disk apparatus. Past researchers used pin-on-disc apparatus to evaluate the effects of various wet, dry, and contaminated conditions on coefficient of friction of rubber-on-steel couples (Cruz Gómez *et al*., 2013). They found that the highest friction was obtained when no contaminant was present with its coefficient of friction varying from 0.6 to 1.2. Zhou *et al*. (2017) studied the static friction of rubber and pipes for pipe-laying operation using a large fixture. They revealed that the types of rubber and normal force applied on steel resulted in different coefficient of friction ranging from 0.5 to 1.5. They reasoned that these fluctuation of static friction because of the interaction between folds and creep deformation. Xie *et al*. (2000) proposed a fixture to investigate the coefficient of friction between workpiece and fixture element.

Recent growth of robot automation in various industries that requires motion in vertical direction, in-situ measurement of friction on vertical surface is required for effective design. Finger clamping unit (Jeon *et al*., 2021), clamp type submarine cable inspection robot (Wang *et al*., 2023) and kiwi harvesting end effector (He *et al*., 2023) were few developed mechanisms that relies on clamp for the necessary actions. The friction force is one of the essential parameters in the design process and operation of a grasping robot (Ciornei *et al*. 2013). Wang *et al*. (2021) proposed an apparatus to simulate a robotic grasping for measuring coefficient of friction of different food materials. Vandal (1997) patented a pole climbing robot for lifting maintenance equipment such as paint sprayers and the like along a vertical tapered pole such as lamp post. Khan and Prabhu (2018) designed a wheeled pole climbing robot with high payload to meet demand of repairs of energy transmission line, scaffolds, and support of lamp post. For construction industry, many equipment and support poles are dusty, rough and degraded under long weather exposure, resulting in unpredictable frictions. Coefficient of friction between different friction materials and vertical structure such as pole is usually varies depending on the condition of the structure, thus hinder the design and development of clamp-based climbing mechanisms or tools. The deformation mechanism of different material might change and contributed to different coefficient of friction when they are positioned vertically.

In this paper, a simple clamp-based apparatus is proposed to determine the coefficient of static friction (COF) from measured clamping force and applied gravitational load. The COF of different materials are evaluated against a lamp pole. Finally, the obtained COFs are discussed and compared with those found from literature.

BACKGROUND THEORY

Static friction force, F_S refers to the maximum force exerted between two contacting surfaces from any relative motion. The two surfaces are maintained in contact by the normal force, F_N. It is typically compared in terms of coefficient of friction, μ, given by the Equation (1). The coefficient of friction depends mainly on the type of materials and the surface condition of the contacting surfaces.

$$F_S = \mu \times F_N \tag{1}$$

Typically, the weight of the object contributed to the normal force to maintain both surfaces in contact. However, when the contact surface between objects is vertically aligned against the gravity, the weight of the movable clamp fixture, F_g must be sustained by the friction force for the object to remain stationary, as illustrated in Figure 1 and Equation (2). Thus, clamping force, F_C is applied equally to the normal force for the friction force to be in action, as given by Equation (3).

$$F_S \geq F_g \tag{2}$$

$$F_C = F_N \quad (3)$$

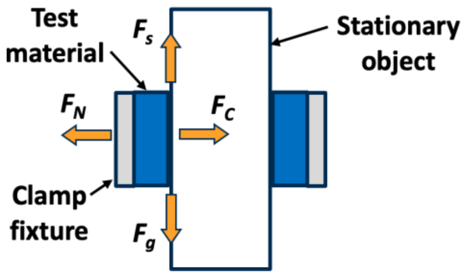


Figure 1. Direction of forces

METHODOLOGY

Measurement Apparatus

Figure 2 (a) shows the proposed measurement apparatus to determine the coefficient of static coefficient based on clamp method for different test materials. The proposed apparatus was prototyped, as shown in Figure 2 (b). The clamp fixture was made of galvanized steel and the sensor mounting was additively fabricated using ABS polymer. The prototype was weighed at 654.43 g.

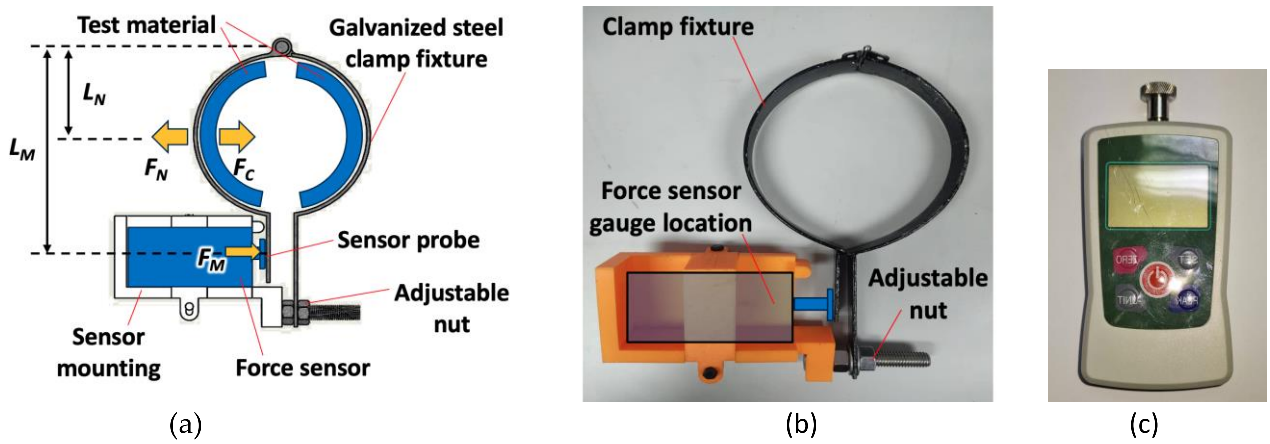
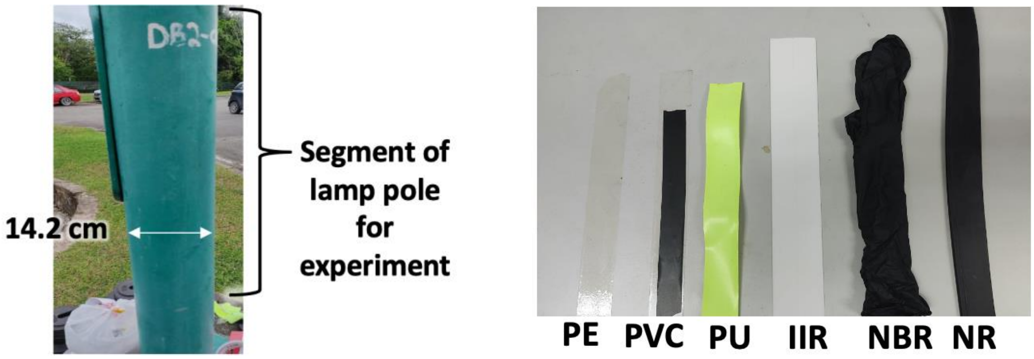


Figure 2. Proposed measurement apparatus (a) concept design, (b) actual design, (c) force gauge

Figure 2(c) shows the digital force gauge (model ZMF-500) that was used to measure the clamping force through a digital display, with its maximum measurement capacity of 500 ± 0.1 N. The force gauge was installed at the sensor mounting, provided at the proposed measurement apparatus in Figure 2. The total weight of the clamp fixture with the force gauge installed is 8.4 N.

Test Materials and Equipment

In this paper, a lamp pole at the Faculty of Engineering, Universiti Malaysia Sabah was selected as the stationary object for experimental purpose, as shown in Figure 3(a). The metallic pole was made of cast iron with a degraded paint finish. The pole has been exposed to weather for at least 5 years. The measured diameter of the selected lamp pole was 14.20 cm. Different commonly available materials from plastic and rubber groups were prepared in strip form, as shown in Figure 3(b). They are polyethylene (PE), polyvinyl chloride (PVC), and polyurethane (PU) in the plastic group. The rubber group consists of butyl rubber (IIR), nitrile rubber (NBR) and natural rubber (NR). These test materials are attached to the proposed apparatus for the frictional force to be evaluated using the proposed test method. The galvanized steel of the clamp is tested when no test material is attached to the proposed clamp apparatus.



(a) (b)

Figure 3. Selected pole as stationary test object and different test materials as movable object.

Test Method

This experiment is to determine the coefficient of static friction (COF) for different materials against a stationary object. The clamping force reading through the force gauge is set to 50 N by tightening the adjustable nut, as shown in Figure 4. Weight blocks of 500 g are added to the apparatus progressively. The maximum weight that the apparatus can sustain before the apparatus begins to slide downwards, is recorded. The experiment is repeated 3 times for each test material and for different clamp force readings of 100 N and 150 N.

Figure 4. Test procedure on the selected pole as stationary test object

The static COF can be determined by Equation (4):

$$\mu_s = k \bullet F_g \ / \ F_M \quad (4)$$

where

$$k = L_N \ / \ L_M \quad (5)$$

F_g refers to the total payload, comprising the recorded weight and the weight of the measurement apparatus, and k is the apparatus constant related to the dimension of the apparatus. L_N and L_M are distances from pivot to center of test material and sensor probe, respectively, as illustrated in Figure 2(a). The apparatus constant can be further calibrated if a known coefficient of friction material is used. The multiple of k and F_g is the factored payload.

RESULTS AND DISCUSSION

Figure 5 shows the relationship between factored payload and clamping force for different test materials. The trend indicates that the factored payload that it can sustain increases proportionally with the increase of clamping force. Therefore, the factored total payload and the clamping force are correlated with linear relationship. The coefficient of determination (R^2) of at least 0.9992, indicates a strong linear relationship. The slope of the linear line represents the coefficient of static coefficient of the test material against the stationary test object, as deduced in Equation 4. The apparatus in this experiment has a constant of 0.4. The error can be deduced due to the resolution of added weight of 500 g (4.9 N). The error can be reduced when progressive weight addition of 100 g or less is made. However, this small weight addition could cause longer experimental time.

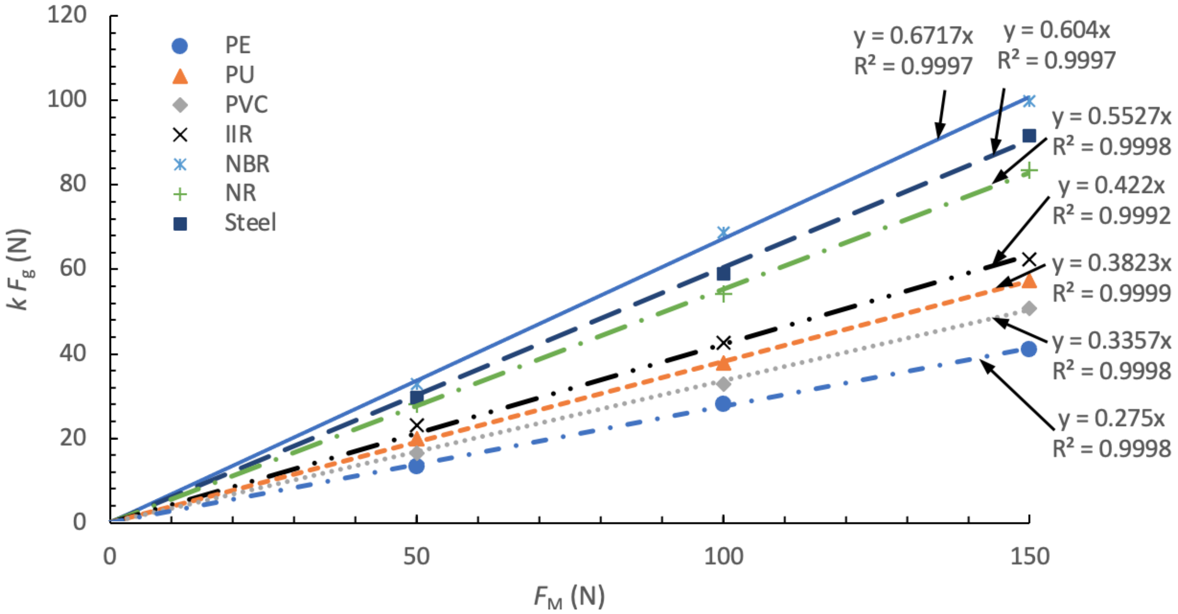


Figure 5. Factored payload sustained by different clamping forces

A more accurate method to obtain the relationship between the factored payload sustained and clamping forces is by measuring the clamping force for a fixed sustained payload. However, the clamping force can only be varied by tightening the adjustable nut manually in the proposed apparatus. The manual adjustment is not recommended as it will cause more fluctuation in reading. Therefore, in this experiment, the test method proposes a fixed clamping force while weight is added progressively instead.

Figure 6 compares the static COF for all test materials, which has been obtained from the slope in Figure 5. The evaluated COF indicates that nitrile rubber has the highest static coefficient of friction of 0.67, follow with natural rubber, butyl rubber, polyurethane, polyvinyl chloride, and polyethylene, in descending order. From this result, it reveals that the rubbers in this experiment, with COF range of 0.42 to 0.67, have higher coefficient of friction that plastics, ranging from 0.28 to 0.38. This can be reasoned that rubber is typically softer and more flexible than many types of plastic (Fukahori *et al.*, 2020). The thicker rubber enables its surface to conform better to irregularities on the opposing surface, creating more contact points, and thus, higher friction. This can be evidenced in Figure 3(b) that rubbers used are thicker than those plastics. Plastic materials are harder and have smoother surface that results in reduced surface contact and, therefore, lower friction. Moreover, rubber has good adhesion properties, which can lead to a stronger grip on certain surfaces, contributing to higher friction.

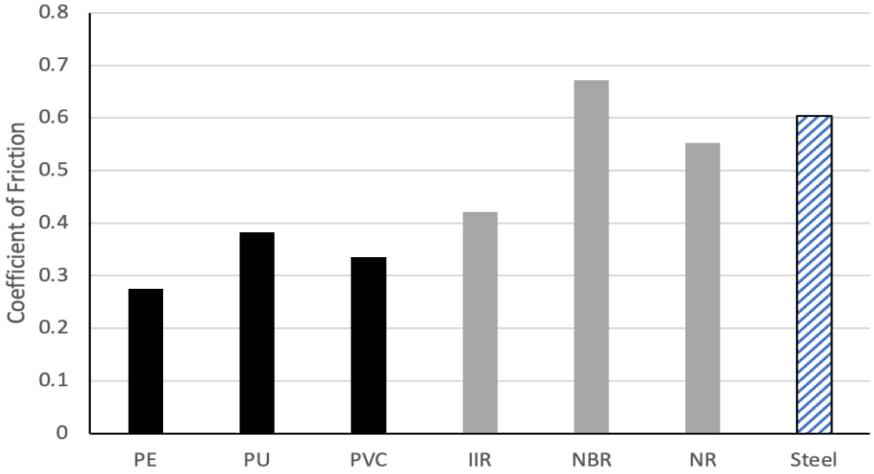


Figure 6. Comparison of coefficient of static friction for different test materials

From Figure 3(b), it is further observed that the natural rubber and nitrile rubber are thicker than the butyl rubber. The difference in thickness for different rubber materials may contribute to the higher coefficient of friction for natural rubber and nitrile rubber than butyl rubber. This resonates with the importance of investigation of coefficient of friction of actual material setup before being implemented to any system, particularly to system that depends on friction as its holding mechanism.

The evaluated COF is compared with those found by other researchers, as shown in Table 1. The COF values are found to be close or within a similar range. The difference between the experimental COF and literature is mainly due to the test being conducted against a dirty steel pole. This confirms that the testing method can be applied to obtain COF value.

Table 1. Comparison of coefficient of friction between experiments and literatures

Test materials	COF	COF (from literatures)	Reference
PE	0.28	0.2 – PE on steel (clean and dry)	Scheneider, 2023
PVC	0.34	0.35 to 0.45 – PVC on steel	Shooter & Tabor, 1952
PU	0.38	-	-
IIR	0.42	-	-
NBR	0.67	0.75 – NBR on SS3161	Shen *et al*., 2015
NR	0.55	0.6 to 1.2 – Rubber tyre on steel (dry)	Cruz Gómez *et al*., 2013
Steel	0.6	0.5 to 0.8 – Steel on steel (clean and dry)	Scheneider, 2023

CONCLUSION

A clamp-based apparatus was designed and applied to determine the coefficient of static friction (COF) based on measured clamping force and applied payload. Due to the configuration of the apparatus, an apparatus constant was introduced to correlate the normal force with the clamping force. Test method using the proposed apparatus was justified and discussed. The COFs of different materials were evaluated against a lamp pole from the slope of the factored payload against clamping force. The study found that rubber materials generally exhibiting higher COF values than plastic materials. The thickness of rubber may play a role in affecting the coefficient of friction. This resonates with the need to investigate the coefficient of friction of actual material setup before being implemented to any clamp-based system, with consideration of environment factors. The obtained COFs were compared and found to be close or within similar range with those in literature. The proposed apparatus can be further improved by implementing a motorized tightening nut to enable progressive change of clamping force in the future.

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REFERENCES

[1] Abdul Halim, N. N., Jaafar, M. H., Kamaruddin, M. A., Kamaruzaman, N. A. & Jamir Singh, P. S. 2020. The causes of Malaysian construction fatalities. *Journal of Sustainability Science and Management*, 15(5), 236–256.

[2] Ciornei, F. C., Alaci, S., Bedrule, R. I. & Drelciuc, C. M. 2013. The Coefficient of Friction, A Basic Parameter in Design and Operation of Robot Grasping. *Robotica & Management*, 18(2), 13-16.

[3] Cruz Gómez, M. A., Gallardo-Hernández, E. A., Vite Torres, M. & Peña Bautista, A. 2013. Rubber steel friction in contaminated contacts. *Wear*, 302(1-2), 1421–1425.

[4] Fukahori, Y., Gabriel, P., Liang, H. & Busfield, J. J. C. 2020. A new generalized philosophy and theory for rubber friction and wear. *Wear*, 446–447, 203166.

[5] He, Z., Li, Z., Diang, X., Li, K., Shi, Y. & Cui, Y. 2023. Design and Experiment of End-Effect For Kiwifruit Harvesting Based on Optimal Picking Parameters, *Inmateh Agricultural Engineering*, 69 (1), 325-334.

[6] Jaafar, M. H., Arifin, K., Aiyub, K., Razman, M. R., Ishak, M. I. S. & Samsurijan, M. S. 2017. Occupational safety and health management in the construction industry: a review. *International Journal of Occupational Safety and Ergonomics*, 24(4), 493-506

[7] Jeon, Y., Oh, J., Kim, J. & Seo, T. 2021. Finger Clamping Unit: A Clamping Device with a Large Clamping Range. *International Journal of Precision Engineering and Manufacturing*, 22, 313-327.

[8] Khan, S. & Prabhu, S. 2018. Design and fabrication of wheeled pole climbing robot with high payload capacity. *2nd International conference on Advances in Mechanical Engineering (ICAME 2018).* 22–24 March, 2018, Kattankulathur, India. pp 012021.

[9] Rodriguez-Arias, H. A. 2019. Low-cost automatic device for obtaining the coefficient of static friction. *Expotecnología 2018 Research, Innovation and Development in Engineering*. 31 October - 2 November 2018, Cartagena, Colombia. pp 012018.

[10] Schneider. 2023. *Coefficient of Friction Reference Chart*. (https://www.schneider-company.com/coefficient-of-friction-reference-chart/). Last accessed on 1 December 2023.

[11] Shen, M.-X., Zhen, J.-P., Meng, X.-K., Li, X. & Peng, X.-D. 2015. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 16(2), 151-160.

[12] Shooter, K. V. & Tabor, D. 1952. The Frictional Properties of Plastics, *Proceedings of the Physical Society, Section B*, 65(9), 666-671.

[13] Vandal, G. R. 1997. *Pole Climbing Robot*. Canadian Patent CA2156702A1.

[14] Wang, Z., Inoue, S., Hashimoto, Y. & Kawamura, S. 2021. Measuring Viscoelasticity and Friction of Tempuras for Robotic Handling, *Journal of Food Engineering*, 310, 110707.

[15] Wang, Z., Wang, Y. & Zhang, B. 2023. Development and Experiment of Clamp Type Submarine Cable Inspection Robot. *Machines*, 11(6), 627.

[16] Xie, W., De Meter, E.C. & Trethewey, M.W. 2000. An experimental evaluation of coefficients of static friction of common workpiece–fixture element pairs. *International Journal of Machine Tools & Manufacture*, 40(4), 467-488.

[17] Zhou, Y.-J., Wang, D.-G., Guo, Y.-B. & Liu, S.-H. 2017. The Static Frictional Behaviors of Rubber for Pipe-Laying Operation. *Applied Science*, 7(8), 760.