EXPERIMENTAL CHARACTERIZATION OF LOW-COST STEEL-POLYMER INTERFACES FOR SLIDING SEISMIC ISOLATION BEARINGS

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Abstract

It is well known that an important impediment to the wide application of seismic isolation is the cost of the isolation bearings relative to the total construction cost. In the case of low-rise residential construction, the cost of the isolation bearings relative to the total construction cost becomes particularly high, mainly because the isolation bearings typically need to accommodate lateral deformation demands similar to those in large, expensive commercial construction or in bridges. In the last 40 years, a significant number of tests have been performed to characterize the friction of polytetrafluoroethylene (PTFE) sliding on mirror-finish stainless steel for use in seismic isolation. However, only a limited number of tests have been performed using low-cost steel-polymer sliding interfaces. Recently, two different low-cost seismic isolation bearings using an inexpensive steel-polymer sliding interface were successfully developed at Stanford University and tested in a full-scale two-story wood frame house, showing the promise of these more economical sliding interfaces. This paper summarizes an experimental program to characterize the tribology, that is, the frictional behavior, of different types of polymers sliding on hot-dip galvanized (HDG) steel. This experimental work was aimed at evaluating the possible use of low-cost isolation bearings under larger vertical loads and improving their tribological characteristics. The main variables studied were: (a) type of polymer; (b) sliding velocity; (c) level of mean pressure; (d) size effects; and (e) cyclic degradation (i.e., the reduction of the coefficient of friction with increasing number of test cycles). More than 200 tests were performed. Results indicate that, at sliding velocities larger than 100 mm/s, inexpensive thermoplastics such as high-density polyethylene (HDPE) or ultra-high-molecular-weight-polyethylene (UHMWPE) sliding on galvanized steel exhibit coefficients of friction similar to those of PTFE sliding on mirror-finish stainless steel. Furthermore, the cyclic degradation of the coefficient of friction observed in UHMWPE sliders is significantly smaller than that observed in PTFE sliders, while both HDPE and UHMWPE sliders showed significantly less signs of wear and delamination than PTFE sliders. These are very promising results, as HDPE and UHMWPE cost approximately one tenth and one fifth of the cost of PTFE, respectively, and, similarly, HDG steel costs less than one third of the cost of mirror-finish stainless steel, leading to significantly more economical seismic isolation bearings.

Keywords: seismic isolation; friction; low cost; residential construction; sliding bearings

1. Introduction

The majority of engineered sliding bearings used for the seismic isolation of structures mainly consist of a steel-polymer sliding interface (i.e., a polymeric surface sliding on a steel surface). The steel surface typically consists of a mirror-finish stainless-steel concave dish, while the polymeric surface typically consists of polytetrafluoroethylene (PTFE, commonly known as Teflon®) or PTFE-based polymer blends, although other engineered polymers have also been used. While these devices have been successfully implemented in a number of high-budget structures, such as hospitals, airports, and bridges, they have not been implemented in low-budget structures, such as low-rise residential buildings, which are many times the most vulnerable structures in seismic events. One of the main impediments to the implementation of sliding bearings in low-budget structures is their high cost. Using inexpensive materials in the sliding interface would help reduce the cost of the bearings and, thus, facilitate their implementation in more structures.

Recently, two different low-cost seismic isolation bearings using an inexpensive steel-polymer sliding interface were successfully developed at Stanford University and tested in a full-scale two-story wood frame house [1]. The materials used in these bearings were high-density polyethylene (HDPE) sliding on galvanized steel, and the pressure at the sliding interface was about 3.8 MPa. The results of the study are highly encouraging for light-frame structures. However, the applicability of these bearings in heavier structures, such as masonry housing, required further study, motivating the study described in this paper.

This paper summarizes a two-phase experimental program of more than 200 tests to characterize the tribology (i.e., the frictional behavior) of different types of polymers sliding on hot-dip galvanized (HDG) steel. Full details about the tests and results have been submitted for peer review and publication [2,3]. Phase 1, described extensively in [2], consisted of characterizing the friction of eight different polymers sliding on HDG steel at a pressure of about 18 MPa, with a particular focus on the relationship between the coefficient of friction, μ, and the instantaneous sliding velocity. One of the polymers tested was the well-known PTFE, which has been studied in much detail and, therefore, is a good benchmark for comparison. The rest of the polymers tested were inexpensive thermoplastics, including variations of HDPE, ultra-high-molecular-weight polyethylene (UHMWPE), polyoxymethylene (POM), and nylon. With the exception of HDPE, all these thermoplastics have been used in a wide range of engineering applications because of their desirable tribological properties, such as durability and relatively low friction. In Phase 2, described extensively in [3], three inexpensive thermoplastics were tested to further characterize their frictional behavior. The main goal was to study the dependence of μ on several parameters such as: pressure, specimen size, and loading history. The results of these tests show promise for the use of these materials in low-cost seismic isolation.

2. Stick-Slip and Instantaneous Velocity

Several related yet different phenomena have been referred to with the term "stick-slip." Among these we can find: the difference between the static and kinetic coefficients of friction, the transition between them (also known as the "Stribeck effect"), the abrupt acceleration that occurs at initiation of motion due to the Stribeck effect, and the intermittent sticking and sliding motion that may occur under certain sliding conditions. The term was coined by Bowden and Leben [4], who originally used to refer to the latter phenomenon. We will use the term "stick-slip" to refer to the variation of friction during sticking or slipping.

Stick-slip is of interest to us because of its effect on the seismic response of the isolated structure. The abrupt changes in stiffness that take place when sticking or slipping occurs in the sliding interface produce high-frequency accelerations in the structure [5,6]. This phenomenon has been observed analytically by Fan et al. [7] and experimentally by Kelly [8] and Jampole et al. [1]. Therefore, we consider it important to characterize the stick-slip behavior of the steel-polymer interfaces. This characterization requires knowledge of how the friction varies instantaneously with sliding velocity.

It has been well established that in steel-polymer interfaces, particularly PTFE sliding on mirror-finish stainless steel, the general trend is that μ increases with sliding velocity. Accordingly, two mathematical models have become popular to describe how μ varies as a function of sliding velocity. The most widely used model, first proposed by Constantinou et al. [9], approximates the sliding coefficient of friction, μ_s,with an exponential equation as

$$\mu_s = f_{\max} - Df \exp\left(-a\left|\dot{U}\right|\right) \tag{1}$$

where $f_{\max}$ is μ at large velocity, Df is the difference between $f_{\max}$ and μ at very low velocity, a is a constant, and $\dot{U}$ is the instantaneous velocity. The other somewhat popular model, first proposed by Chang et al. [10] based on Perzyna's viscoplasticity theory [11], approximates the friction force using a logarithmic equation, which Dolce et al. [12] adapted to

$$\mu = \begin{cases} a + b \cdot \ln(v) & v > 3 \text{ mm/s} \\ a + b \cdot \ln(3) & v \leq 3 \text{ mm/s} \end{cases} \tag{2}$$

where a and b are constants, and v is the sliding velocity.

Both models have been used to compute instantaneous μ as a function of instantaneous sliding velocity. However, they have been empirically calibrated with summary test data (e.g., taking the peak velocity of each test), which does not necessarily represent the instantaneous nature of stick-slip. It was paramount for our study to use instantaneous data—not summary data—when describing the variation of μ with sliding velocity.

3. Experimental Program

In order to measure the coefficient of friction, two known forces must be applied: one in the direction normal to the sliding interface and the other in the tangential direction. To achieve that, the tests were carried in double shear, that is, one moving body moved tangentially to two fixed bodies (one on each side), creating two sliding interfaces. The moving body was a thick steel plate to which sheets of HDG steel were attached on each side. The fixed bodies were two thick steel plates attached to a strong T-slot table, each holding a polymer specimen in place. The normal force was applied with a hydraulic jack, measured with a 100 kN load cell sandwiched between the jack and the sliding interfaces, and sustained throughout the tests with prestressed rods. The tangential force was applied with a 250 kN MTS actuator in the vertical direction.

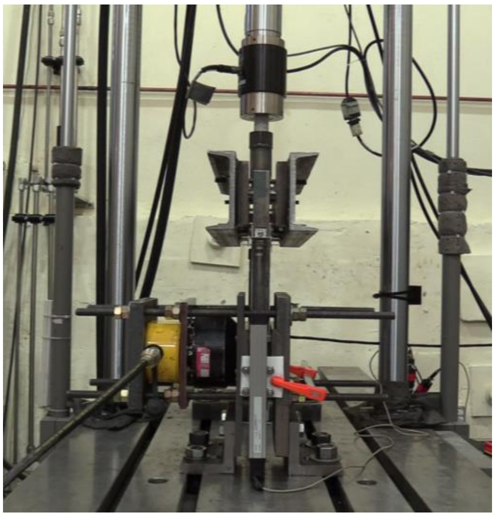

Fig. 1 – Testing apparatus

The maximum speed that the actuator could move was about 50 mm/s. Based on previous experiments done with PTFE [13], we expected μ to vary significantly with sliding velocity up to speeds between 100 and 200 mm/s. Therefore, to fully characterize the variation of μ with sliding velocity, we needed sliding velocities above 200 mm/s. We accomplished this by constructing a motion amplifier, consisting of two stiff steel channel beams, which amplified the motion—and reduced the tangential force—by a factor of 6.9. The motion at the sliding interface was monitored through an LVDT, which measured the relative displacement between the HDG steel specimens and the polymer specimens. All data were sampled at about 102 Hz.

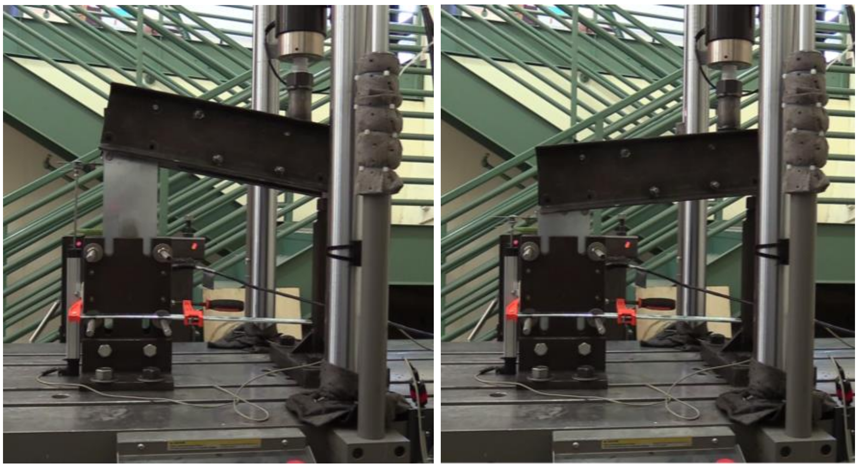

Fig. 2 – Movement of testing apparatus

The testing apparatus used in Phase 2 was essentially the same as in Phase 1. Some minor improvements were made to ease the process of setting up and changing specimens. Perhaps the most significant change was the way the polymer specimens were held in place. In Phase 1, each specimen was clamped by two small steel plates—one at the bottom and the other at the top. In Phase 2, each specimen was inserted into small steel plate that had a hole of the same size of the specimen, thus confining the specimen in all directions. The difference between Phase 1 and Phase 2 lies in the testing variables, which are summarized in Table 1.

Table 1 – Comparison of Phase 1 and Phase 2 experimental designs

Variable	**Phase 1**	**Phase 2**
Polymers tested	Rough HDPE Layed HDPE PTFE Oil-filled nylon POM Glass-filled UHMWPE Oil-filled UHMWPE Diamond-pattern HDPE	Smooth HDPE Rough HDPE Glass-filled UHMWPE
Polymer specimen shape	Square	Round
Polymer specimen thickness	9.53 mm	12.77 mm
Polymer specimen area	4,032 mm^2	2,027 – 8107 mm^2
HDG steel specimen thickness	2.44 mm	2.77 mm
Test protocols	Short-Duration Harmonic	Harmonic Triangular Modified-Sinusoidal
Pressure	18 MPa	3 – 38 MPa
Maximum sliding velocity	350 mm/s	200 mm/s

4. Results

Some important results are summarized in this section.

4.1 Stick-Slip

When the sliding interface is at rest, a relatively high force may be required to initiate movement. This effect, which has been referred to by different names (such as “breakaway effect,” “static friction,” and “stick-slip”), has been observed by many other researchers. However, despite widespread knowledge of the phenomenon and its possibly detrimental effect on the structural response, very little is known about its details. Some of our observations help better understand and model stick-slip.

First, the high friction force required to initiate movement does not disappear immediately once sliding begins but reduces as sliding occurs, resulting in a transient “stick-slip effect.” For this reason, the highest coefficient of friction was consistently observed slightly after the initiation of movement, when the stick-slip effect had not yet fully subsided and the instantaneous sliding velocity was large.

Second, while the stick-slip effect is taking place, the value of the coefficient of friction cannot be described uniquely as a function of sliding velocity. Several models describe the transition between the high coefficient of friction required to initiate movement and a lower coefficient of friction after sliding begins as a reversible function of sliding velocity—a curve sometimes referred to as the “Stribeck curve” [14,15]. However, these models are inconsistent with our results. Rather, our results support what can be concluded from others’ studies: that the Stribeck curve was developed for lubricated interfaces and that, even under a constant pressure, other variables—besides sliding velocity—affect the coefficient of friction during the stick-slip of dry interfaces [16–27].

Third, all of the tested polymers experience the stick-slip effect at every motion reversal. We found that, while the effect may be more pronounced in the first instance of sliding, it never disappears. In PTFE, in particular, the effect is so subtle it can easily be missed, but it can be clearly seen with careful evaluation. In other polymers, especially UHMWPE, the effect is much more pronounced.

Finally, the stick-slip effect occurs when the direction of motion is reversed but not when sliding initiates in the same direction in which it was taking place prior to stopping. This novel observation suggests that there is an elastic component in the stick-slip phenomenon. The test protocol used in order to determine this is shown in Fig. 3 along with the resulting normalized load-displacement plot (where F_f is the friction force at each sliding interface and F_n is the normal force) when performed using glass-filled UHMWPE.

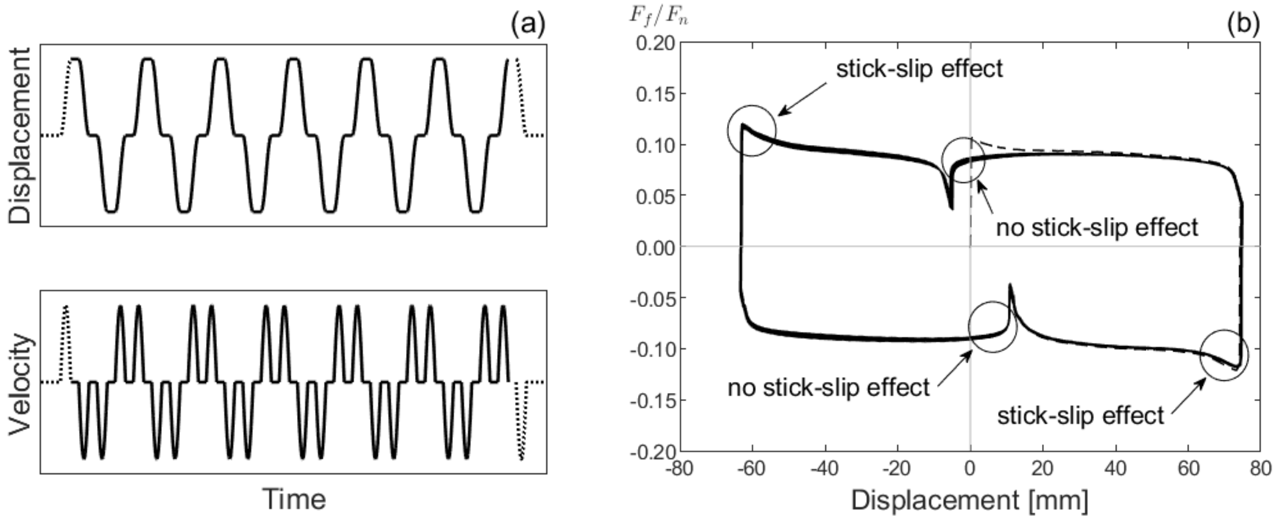

Fig. 3 – Load protocol (a) and normalized load-displacement plot (b) of modified sinusoidal test of glass-filled UHMWPE, illustrating the effect of the previous direction of sliding on stick-slip

4.2 Values of μ

In PTFE and polyethylenes (variations of HDPE and UHMWPE), once the stick-slip effect has subsided—e.g., as sliding decelerates or after a non-reversing stop—the coefficient of friction under a given pressure can be expressed very accurately as a function of sliding velocity. Fig. 4 shows the instantaneous μ-velocity data points for the decelerating portion of the second half cycle of several harmonic tests having different frequencies and, therefore, different accelerations and peak velocities. The data from different tests of the same polymer overlap very well. We fit the data to two models: a logarithmic model (based on [12]) and an exponential model (based on [9]). We found that the logarithmic model fits the data slightly better than the exponential model. Furthermore, our fitted logarithmic model for PTFE matches very well the logarithmic model fitted by Dolce et al. [12] using PTFE sliding on mirror-finish stainless steel at about the same pressure (shown in Fig. 4). The fact that our fitted model matches that of Dolce et al. [12] means that, at least at a pressure around 18 MPa, the friction of PTFE sliding on galvanized steel is practically the same as that of PTFE sliding on the much costlier mirror-finish stainless steel. It also means that the method of using peak velocities—as in [12]—to obtain a μ-velocity relationship for steel-polymer interfaces is accurate when the stick-slip effect has subsided.

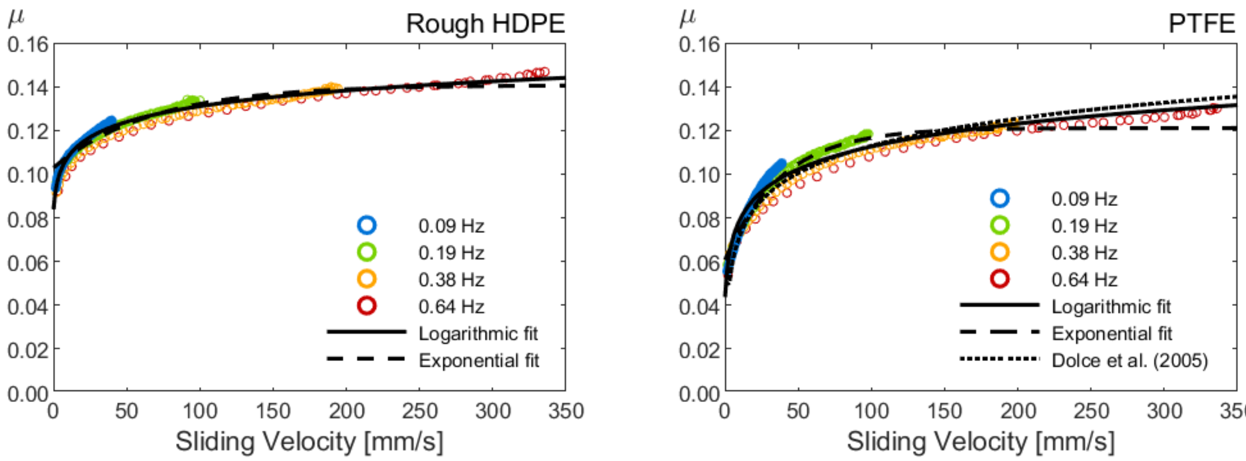

Fig. 4 – Variation of μ with sliding velocity in harmonic tests having different frequencies

Another important observation from our experimental program is related to the values of μ in low-cost polymers in comparison to those in PTFE. Fig. 5 shows the fitted logarithmic μ-velocity models for some inexpensive thermoplastics and for PTFE. We observe that, at very low velocities, the coefficient of friction of PTFE is much lower than that of the other polymers. For example, the coefficient of friction of rough HDPE at very low velocities is twice that of PTFE. However, as the sliding velocity increases, the value of μ for PTFE increases relatively quickly and rapidly approaches the range of μ-values of the other polymers. The result is that, at large sliding velocities, all the polymers have similar values of μ. For example, at sliding velocities larger than 100 mm/s, the values of μ in the inexpensive thermoplastics are all within ±15% from those in PTFE.

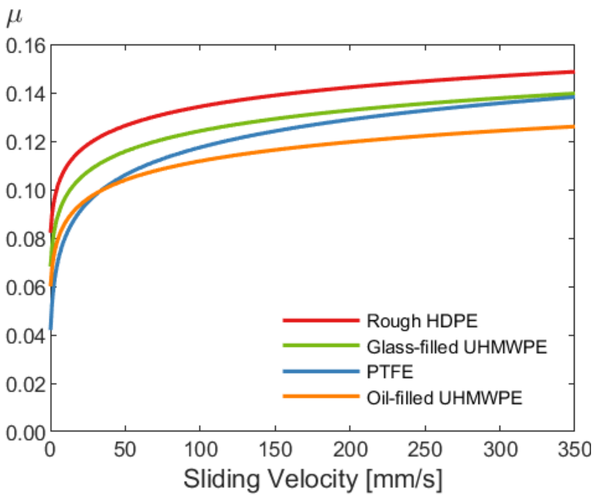

Fig. 5 – Fitted logarithmic μ-velocity models for several polymers at 18 MPa

4.3 Wear

During tests with multiple cycles of motion, the coefficient of friction decreased throughout each test. We determined that this progressive reduction in μ is a result of a transient rise in temperature at the sliding interface and not necessarily due to wear of the sliding interface (see Fig. 6).

Fig. 6 shows the normalized load-displacement plots of two consecutive tests of rough HDPE. The plot on the left side of the figure corresponds to a test with 20 fully reversed cycles (labeled Test #6). The plot on the right side of the figure corresponds to a test with 6 fully reversed cycles (labeled Test #7), performed only about two minutes after Test #6, using the same specimens and without cleaning the interface. Horizontal lines are drawn at the maximum positive and negative values of normalized friction force in the first cycle of Test #6. The fact that these values practically coincide with those of Test #7 demonstrates that the reduction in μ experienced throughout Test #6 is not permanent but disappears after a short period of cooling. Although we did not measure the temperature at the sliding interface during the tests—something that is, in fact, practically impossible to do [28,29]—it has been well established that heating occurs during sliding and that it reduces μ. However, at least in the case of HDPE and UHMWPE, the frictional heating experienced while sliding did not appear to result in any permanent wear that would affect the frictional behavior of the materials. Furthermore, in the case of oil-filled UHMWPE, the reduction in μ caused by frictional heating was practically negligible.

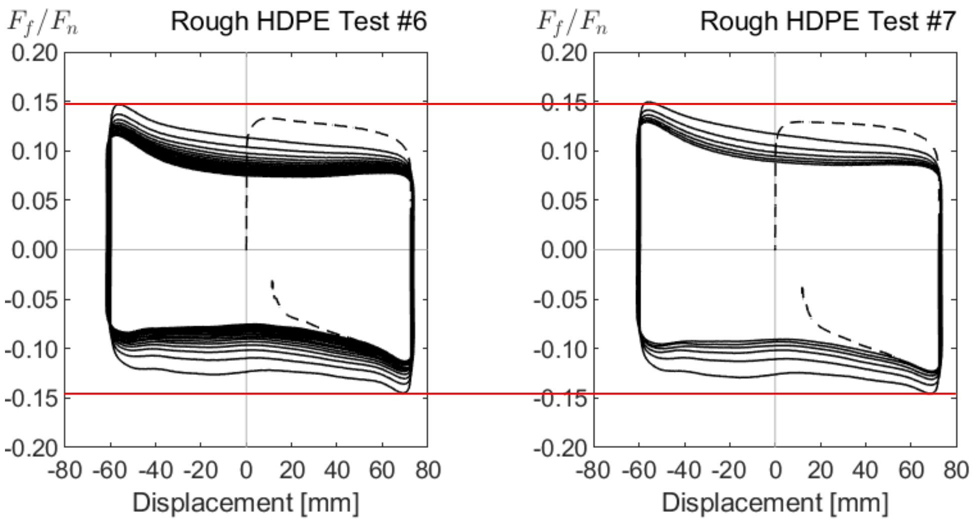

Fig. 6 – Normalized load-displacement plots from two consecutive tests of rough HDPE

For the most part, no significant signs of wear or deterioration were observed in the polymers or the galvanized steel specimens. The only sign of wear observed in the polymers was slight darkening of the surface. The exception to this observation was PTFE, in which significant delamination, or flaking, was observed. This delamination in unfilled PTFE has been observed consistently in past studies [13,30–33], although the use of fillers may mitigate it [34]. In addition, the PTFE specimens were the only ones that experienced significant plastic deformation under an applied normal pressure of 18 MPa. A photograph of worn PTFE specimens after testing is shown in Fig. 7.

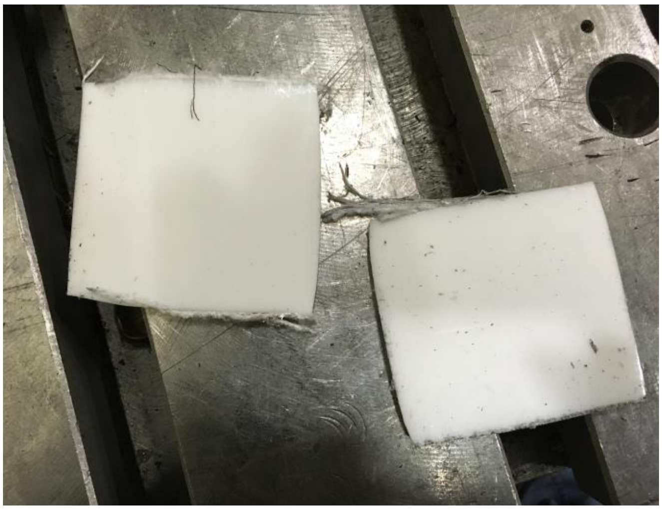

Fig. 7 – Delamination in PTFE specimens

4.4 Pressure

In order to eventually design sliding bearings using the inexpensive polymers studied here, it is necessary to study how their frictional behavior changes with variables that have been shown to influence the frictional behavior steel-polymer interfaces, such as the pressure at the interface. With this objective, we performed tests under different levels of normal pressure. We observed that, in the range of pressures between 7 MPa and 38 MPa, μ varies approximately linearly with the pressure at the sliding interface (see Fig. 8). We also observed that the dependency of μ on pressure—i.e., how much μ varies with varying pressure—varies with sliding velocity. For example, in glass-filled UHMWPE, the level of pressure has a much more significant effect on μ at high velocities (μ_{HV}) than at very low velocities (μ_{LV}). Furthermore, these dependencies vary by polymer, too.

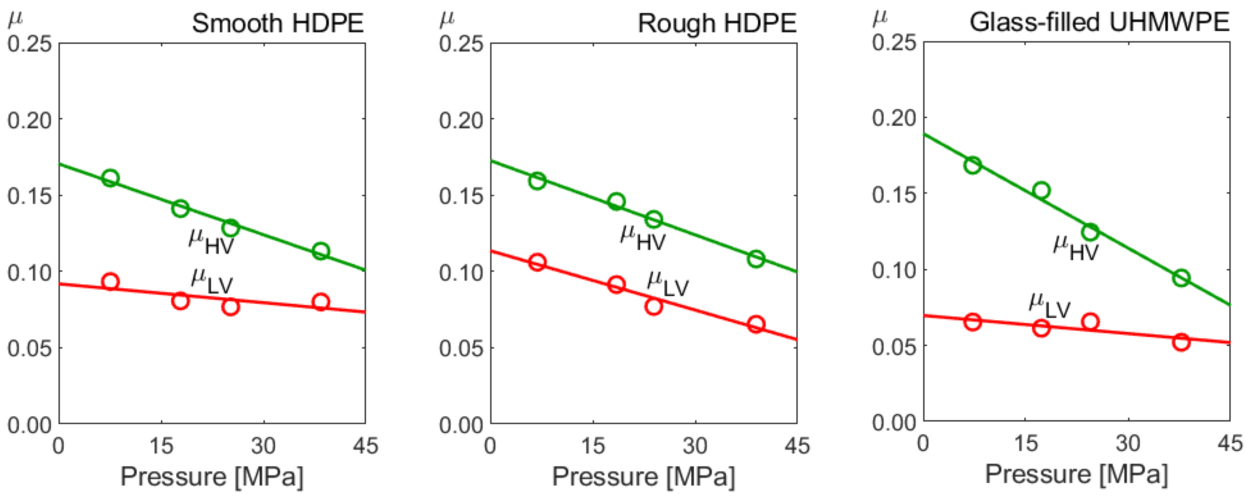

Fig. 8 – Variation of μ with pressure in different polymers

5. Summary and Conclusions

A two-phase experimental program was carried out in order to characterize the frictional behavior of several inexpensive polymers sliding on hot-dip galvanized (HDG) steel. Among the tribological properties studied were: the instantaneous variation of friction with sliding velocity, the dependence of stick-slip on the previous direction of sliding, the wear of the sliding interfaces, and the variation of friction with pressure.

We found that, when compared to the widely used PTFE, the tested low-cost polyethylenes (variations of HDPE and UHMWPE) sliding on HDG steel: (1) have similar coefficients of friction at sliding velocities larger than 100 mm/s, (2) have a much better resistance to wear, and (3) have a much more pronounced increase in friction when the sliding direction is reversed. We also conclude that, at a given pressure, μ can be very accurately approximated as a logarithmic function of the instantaneous sliding velocity, although only once the effect of reversing the direction of sliding has subsided. Additionally, we observed that the values of μ of PTFE sliding on HDG steel are practically the same as those of PTFE sliding on mirror-finished stainless steel, indicating that—at least at the tested pressure (about 18 MPa)—the change from mirror-finish stainless steel to HDG steel would have little to no effect on the frictional behavior. More details and conclusions from the experimental program can be found in [2] and [3], but the ones mentioned above highlight the feasibility of using these low-cost interfaces in seismic isolation, as well as possible areas for further study.

These results are very encouraging for the possible implementation of seismic isolation in low- and mid-rise residential structures, considering that HDPE and UHMWPE cost approximately one tenth and one fifth of the cost of PTFE, respectively, and, similarly, HDG steel costs less than one third of the cost of mirror-finish stainless steel. Furthermore, the data from the results enable a more accurate modelling of these low-cost steel-polymer interfaces, so the response of the isolated structure can be evaluated analytically with more confidence.

6. Acknowledgements

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