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Cyclic loading and marine environment effects on the properties of HDPE umbilical cables

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Abstract This work presents a study of the effects of cyclic loading and marine environment on the mechanical properties of high-density polyethylene (HDPE) used in the external layer of submarine cables. Two different types of samples were tested. The first type was tested in the as-received condition whereas the second one was taken from the cyclic-loaded material. The cyclic-load test was carried out in a device, according to the API 17E standard (API 17E-98, Specification for sub sea production control umbilicas). These samples were submitted to a process of artificial aging. All the specimens were submitted to tensile test and the analysis and comparison of the results showed that HDPE suffered alterations in its mechanical behavior, especially the material submitted to cyclic loading. Both aged and as-received samples were observed by using scanning electron microscopy and their hardness was also measured. The results showed that the cyclic loading, the seawater and the ultraviolet radiations accelerated the degradation process of HDPE.

Introduction

The optical-power submarine cables, named umbilical cables, are utilized to transmit control signs and to supply electric power for the underwater equipment named Christmas trees (ISO 10423:2003) [2]. This equipment is placed at wellhead for the control of oil and gas production or injection on the sea bottom. The typical structure of an umbilical cable is shown in Fig. 1. It is composed of an overlap of plastic, metal structure layers and cables made of copper and optical fiber. The external polymeric layer composed of high-density polyethylene (HDPE), which is usually extruded on the external traction armor. This polymeric layer makes the cable watertight, protecting the internal structure against corrosion, abrasion and impact damages. After that it helps to maintain the traction armor wires in the right position [3]. The cable failure can result in disastrous consequences from the economic point of view, because it can bring to an end the perforation and production operations. The umbilical cables are usually affected by different conditions of the environment along their length, as illustrated in Fig. 2. Area 1 represents the external layer of the cable submitted to the solar radiation between the floating production system (FPS) and the sea surface. Area 2 represents the region of the cable located under the water but near the sea surface, which is submitted both to solar radiation and the seawater effects. Finally, area 3 represents the region of the cable, which is only affected by the seawater. This region is near the sea bottom.

Research [4] has shown that most polymers, such as HDPE, are sensitive to the environment. The ultraviolet radiation and the oxygen interact with the surface of the polymers causing their degradation. Quintela and Alves studied the influence of the external natural agents such as solar radiation and sea environment on the HDPE external layer of the flexible lines [5]. They concluded that the aging process causes a decrease in the maximum load that samples can stand during tensile tests. Other works also show these deleterious effects in some polymers [6, 7]. It has also showed that stresses and a rise in the temperature

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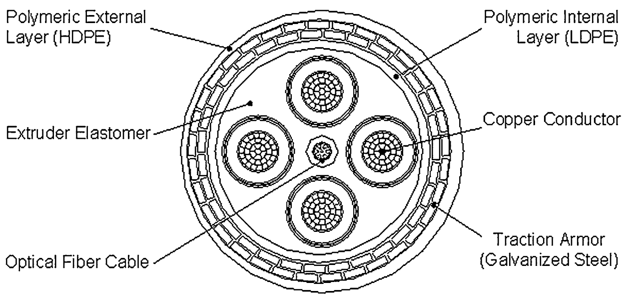


Fig. 1 Schematic illustration of typical structure of an umbilical cable (cross section)

could accelerate the chemical reactions involved in the degradation process. Temperature also influences on mechanical behavior [4]. Moreover the temperature gradient increases the stress applied on the material [4].

As well as the environment conditions, the sea currents also affect the cables, as these cause lateral displacements of the platforms and movements of the lines along the cables. These displacements generate traction, bending, torsion and external pressure on the umbilical cable. Stress applied to material can cause changes in molecular entanglements or cross-links that can lead to constrain [4]. Therefore, the stress caused by displacements, in combination with the seawater and the ultraviolet radiation can lead to premature failure of the external polymeric layer. Thus, reducing umbilical cable service lifetime [3, 4].

Fatigue is also a phenomenon observed in polymers. Furthermore, the fatigue crack propagation in high-density polyethylene (HDPE) is a nonmonotonic function of the energy release rate, which is observed in other semicrystalline polymers. The crack propagation involves both crazy formation and large scale yielding as competitive mechanisms. The characteristics of polymers are also important to understand their mechanical behavior. Low and high-density polyethylene present differences on

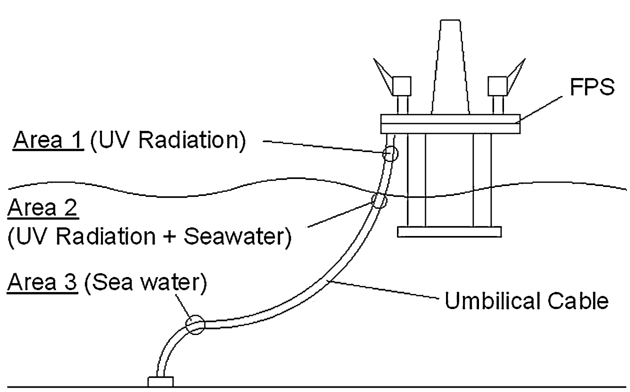


Fig. 2 Environmental conditions during working life of HDPE cable in FPS

fatigue behavior [8]. Additionally, mechanical behavior of polymers are also both time and temperature dependent. The HDPE strain time dependency is prominent in the region of high stress concentration [9]. Cárdenas and Gonçalves studied the influence of the cyclic loading on the umbilical cable external polymeric layer (HDPE) [3]. The results of the tensile test showed that the cyclic loading had a strong influence in the mechanical properties of the external layer of the cable, causing a great decrease in the material toughness. These tests did not analyze the effect of fracture mechanisms as showed in other works [9–11].

Meyer and Pruitt also studied the combined influence of the cyclic loading and the γ-radiation on the ultra-high-molecular-weight extruded polyethylene (UHMWPE) [12]. The tests showed that the increment in the number of load cycles and in the magnitude of the deformation caused an increase of the residual plastic strain. The results also showed a decrease in the material density as well as an increase in micropore and crack formation. In that work, the increase in the lamellae alignment due to the load applied was also observed.

As a conclusion, the combination of stress, strain, cyclic loading, temperature and the strain time dependence seems to accelerate polymers' degradation. This work describes accelerated tests, simulating about 20 years of service lifetime, of HDPE in external layer of umbilical cables. The effect of the cyclic loading, the seawater and of the ultraviolet radiation on the mechanical properties of the external polymeric layer of umbilical cables is also analyzed. Thus, the weathering degradation is here analyzed by placing the specimens in conditions similar to the service. The crack propagation in fatigue is not analyzed in this study.

Material and methods

Material

The material studied in this work was a high-density polyethylene that composes the external layer of an umbilical cable. This layer was extruded on the traction armor of the cable. The layer thickness was 5 mm and the external diameter of the cable was 108 mm. The materials properties were according to ASTM D 150-98 [13], ASTM D 638-03 [14], ASTM D 746-04 [15], ASTM D 792-00 [16], ASTM D 1238-04 [17], ASTM D 1505-03 [18], ASTM D 1693-05 [19], ASTM D 3895-04 [20] standards.

The samples submitted to aging were manufactured from two different types of HDPE cables. The first type of samples was taken from the cable in the as-received condition and the second type of samples from the cyclic-loaded cable. The samples were submitted to tensile tests and hardness tests. Finally, they were observed by using scanning electron microscopy (SEM) to study the effect of the aging and the cyclic loading HDPE surface. Eighteen samples for tensile tests were manufactured, nine were taken from the cable in the as-received condition and nine were taken from traction parts of the cyclic-loaded cable. Six samples for tensile tests were aged in each device, three of which were aged in the as-received condition and the other three in the cyclic-loaded condition. Specimens in the as-received and in the cyclic-loaded condition for hardness tests and SEM observation were also placed and aged in the same conditions.

Umbilical cable cyclic loading test

The umbilical cable cyclic loading test was carried out to simulate the several and complex stresses that the umbilical cables are submitted to during installation and service in offshore operations. The test was carried out in a special device designed and manufactured according to API 17E-98 standard [1]. The cable tested was 13.5 m in length and 108 mm in diameter. The cable was placed in the device showed in Fig. 3 and 600 kN of traction load was applied. During the test, the sheave of the cyclic-loaded device, which was 3.5 m in diameter (illustrated in Fig. 3), was pulled and released in alternate movements. The curve in the cable resulted in cyclical stresses and strains in its different layers. The displacement of the cable during the test was about 1.8 m in each cycle. The complete cyclic loading test took 30,000 cycles, and each cycle was between 5 and 10 s long, or about 80 h. The main objective of this test was to obtain a material similar to one after approximately 20 years' service. Crack formation and propagation were not expected in these tests conditions.

Artificial aging of HDPE

In order to simulate the weathering of the HDPE layer of the umbilical cable in service caused by natural environment, three sets of accelerated aging tests were developed in the laboratory. The procedure is described as follows. The first set of test carried out corresponds to Area 1 in Fig. 2, in which the HDPE is under ultraviolet radiation. The device used to carry out this test was composed of fluorescent lamps that emit radiation ranging from 320 to 390 nm wave length, which is similar to solar radiation. The tests were according to the ASTM D 4329-99 and ASTM G 154-00a standards [21, 22]. There was not a replacement of oxygen in thermal vat or agitation. The radiation was maintained 24 h a day.

The simulation of the second area (Area 2) in Fig. 2, in which the HDPE is under ultraviolet radiation and seawater, was carried out by placing the specimens inside of a thermal vat containing artificial seawater, which was prepared as described in ASTM D 1141-98 standard [23]. Simultaneously, the specimens were irradiated with ultraviolet radiation during the testing time.

The third set of tests carried out corresponds to Area 3 in Fig. 2, in which the HDPE is under the seawater. The specimens were placed inside a thermal vat containing artificial seawater [23]. In this case, the specimens were not irradiated, unlike the two previous sets. The specimens were isolated in a dark area.

The accelerated aging tests were carried out for 500 h and the temperature of the device was maintained at (35 ± 1) °C. Temperature control was vital so as not to allow another variable.

Hardness tests Type D

A Type D (Digital)-DU-010 durometer was used to test the material. The hardness tests were carried out according to the ASTM D 2240-03 standard [24]. The samples for hardness tests were a strip type of 5 mm thick, 20 mm wide and 75 mm long. They were conditioned for 40 hours before the test at (23 ± 2) °C and at a relative humidity of (55 ± 5)%. Five measurements for each specimen were carried out. The average and standard deviation were calculated.

The HDPE samples were tested in 8 (eight) different conditions, as follows: in the as-received condition, in the as-received condition aged under ultraviolet radiation, in

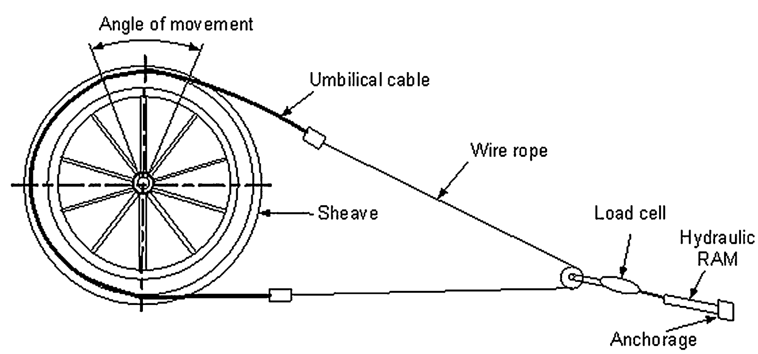


Fig. 3 Schematic illustration of the device for umbilical cable cyclic-load test according to figure I-2 of Appendix I-Fatigue Testing API 17 E

the as-received condition aged in seawater, in the as-received condition aged under ultraviolet radiation and seawater simultaneously; in the cyclic-loaded condition, in the cyclic-loaded condition aged under ultraviolet radiation, in the cyclic-loaded condition aged in seawater, in the cyclic-loaded condition aged under ultraviolet radiation and seawater simultaneously.

Tensile tests

The tensile tests were carried out according to the ASTM D 638-03 standard [14]. The tests were carried out by using an INSTRON TTL-DM-L screw-driver mechanical test system. The speed used in the tests was 50 mm/min, which corresponds to an average value of speed recommended in the ASTM D 638-03 standard [14]. Tensile test specimens were manufactured according to ASTM D 638-03 standard [14], as illustrated in Fig. 4. The HDPE samples were tested in the same conditions as described in the section ''Hardness tests Type D''.

Scanning electron microscopy (SEM)

The effect of the cyclic loading, the ultraviolet radiation and seawater in the surface of HDPE samples in different test conditions were observed by using a scanning electron microscopy (Stereoscan 440, LEO). The HDPE samples observed were tested in the same conditions as described in the section ''Hardness tests Type D''.

Results and discussion

Tensile tests

The cyclic-loading tests were carried out through the device showed in Fig. 3. Figure 5 (material a) and 6 (material a) show the stress-strain representative curves of the as-received and cyclic-loaded samples, respectively.

A yield drop in tension from around 21 MPa to 14 MPa could be observed in the as-received samples during yielding after an average strain of 60%. A uniform necking was also observed and could originate a reorientation in the polymeric chains in the HDPE sample [25–27]. The strain-

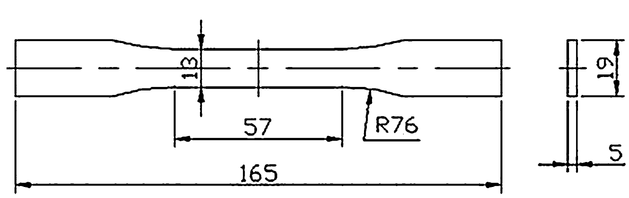


Fig. 4 Specimen for tensile test according to the ASTM D 638 standard

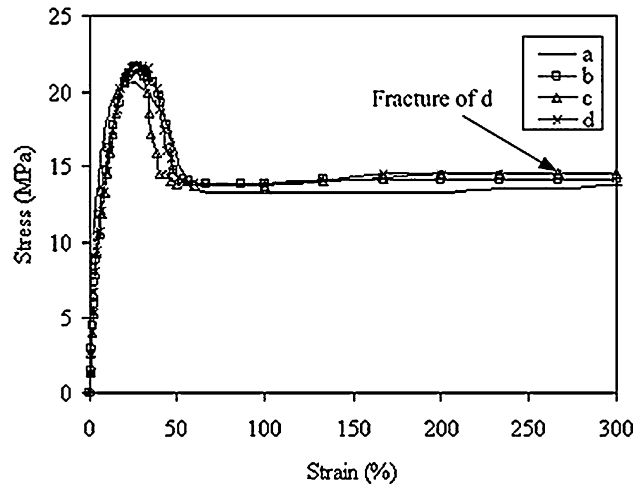


Fig. 5 Stress–strain curve of the specimen of HDPE, material in the as-received condition: (**a**) as-received; (**b**) aged under ultraviolet radiation; (**c**) aged inside artificial seawater; (**d**) aged under ultraviolet radiation and inside the seawater simultaneously, the rupture occurred before a strain of 300%. A uniform necking was observed and originated a reorientation in the polymeric chains in the HDPE specimen

stress curve presented a plateau as can be observed in Fig. 5. However, a small and steady rise was observed in the strain–stress curve probably due to the reorientation phenomenon [25–27]. The test was interrupted before the rupture of the as-received samples. The strain reached during tensile test was of 300% and no specimen rupture was observed. A similar behavior was observed in all tensile tests carried out to evaluate as-received specimens aged under ultraviolet radiation and inside the artificial seawater as can be observed in Fig. 5 (materials b and c). However, both the specimens aged under ultraviolet radiation and inside the artificial seawater showed a different behavior. The rupture was detected before 300% of strain was reached as can be seen in Fig. 5 (material d). Hence the degradation process was accelerated when the two different conditions were used simultaneously.

A yield drop in tension from around 21 MPa to 14 MPa could also be observed in the cyclic-loaded samples during yielding after an average strain of 60% as can be observed in Fig. 6. The rupture was detected just after the same amount of strain, as showed above. In this case, a non-uniform necking was observed. The strain-stress curve did not present a plateau. A similar behavior and result were observed in all types of specimens tested as can be seem in Fig. 6.

The results of the tensile tests showed that the cyclic loading had a significant effect on the decrease of the HDPE mechanical properties, mainly in the toughness and ultimate elongation. Therefore, the elongation characterized the damage. The strength did not change after cyclic-loading test. This behavior is frequently observed even

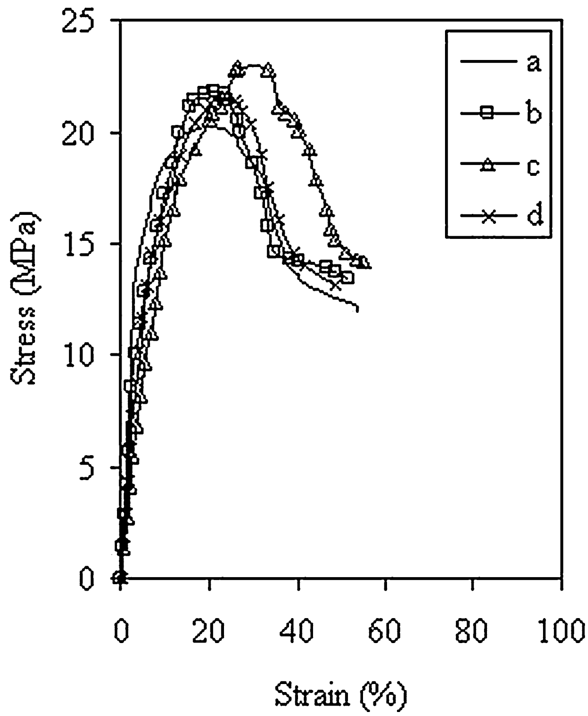


Fig. 6 Stress–strain curve for the specimen of HDPE, material in the cyclic-loaded condition: (**a**) no aged; (**b**) aged under ultraviolet radiation; (**c**) aged inside artificial seawater; (**d**) aged under ultraviolet radiation and inside artificial seawater simultaneously. A nonuniform necking was observed. The strain-stress curve did not present a plateau

after prolonged exposure, whereas the elongation to break is usually a fairly sensitive indicator of degradation and it often correlates quite closely with the damage during service lifetime. It is likely that, partially aligned molecules, which case a decrease in the entropy of the material [28]. Another work [29] showed similar behavior of cyclic-loaded and as-received material of this study. The effect of the cyclic loading combined with the effects of the two environment agents mentioned, i.e., ultraviolet radiation and seawater caused the major damage measured in these tensile. However, the damage could only be directly observed by using scanning electron microscopy as described in the section ''Scanning Electron Microscopy''.

An increase in temperature was also verified during the tests but not measured. This effect was related to the viscous part mechanism of deformation where energy is lost as heat [28]. No viscoelastic analysis of the load-displacement curves during the cyclic-loading test was carried out in this work in order to illustrate this phenomenon.

Hardness tests type D

The results of the type D hardness measurements (ASTM D 2240-03) [24] in different samples of HDPE are shown in Table 1. The values of type D hardness measurements were

Table 1 Results of the Type D hardness tests. HDPE samples in the as-received condition were indicated as follows: 1—as-received, 3—aged under ultraviolet radiation, 5—aged inside the artificial seawater, 7—aged under ultraviolet radiation and inside the artificial seawater simultaneously. HDPE samples in the cyclic-loaded condition were indicated as follows: 2—as-received after cyclic-loaded test, 4—aged under ultraviolet radiation, 6—aged inside the artificial seawater, 8—aged under ultraviolet radiation and inside the artificial seawater simultaneously. (*) Average of five measurements. The standard deviation was D/1

Specimen	Hardness (*)
1	D/63
2	D/62
3	D/62
4	D/62
5	D/60
6	D/64
7	D/64
8	D/62

the average value of 5 (five) measurements in each sample. The hardness measurements were between D/64 and D/60. After aging, the results of measurements presented a slight variation, mainly in the as-received condition. These results were not expected because stiffness changes frequently accompany the degradation process. The explanation could be related to molecular alignment during processing. Therefore the hardness test was not sensitive enough to show the damage caused even after the cyclic-loading test in this work. Environmental factors like ultraviolet radiation and seawater on HDPE surface were also not directly measured. It was likely that, the weathering effects were concentrated on the surface. Moreover, the strength was less affected than the elongation of the material, as observed during tensile tests.

Scanning electron microscopy (SEM)

The influence of the cyclic loading, the ultraviolet radiation and seawater in the HDPE surface exposed was observed by using scanning electron microscopy. Figures 7 and 8 show the specimens in different conditions. Two different regions were observed, the traverse section and the external surface of the sample, which was exposed to the different environments. However, the traverse section showed hardly any differences among all the samples observed. The most severe damage was expected to be near the surface [4].

The samples surface showed a slight alignment in the HDPE cyclic-loaded condition, as can be seen in Fig. 7b. This is not present in Fig. 7a, where the HDPE as-received specimen can be observed.

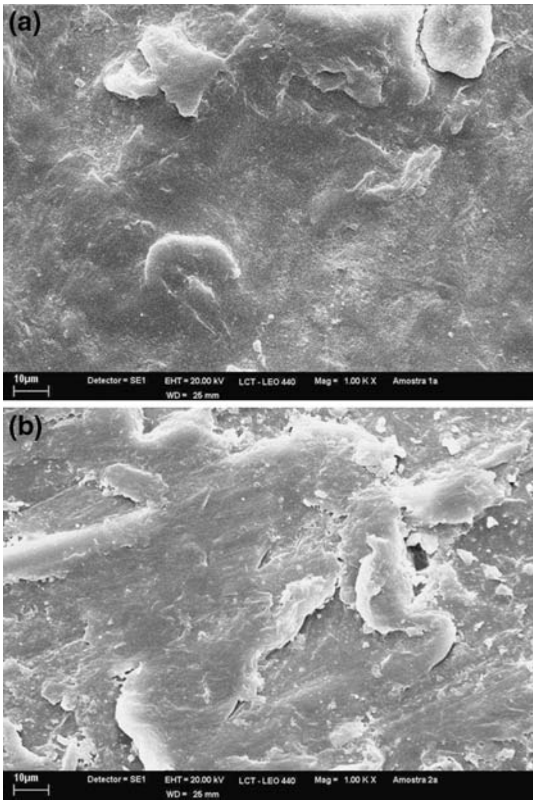


Fig. 7 Scanning electron microscopy of surface of the HDPE samples of: (**a**) material in the as-received condition; (**b**) material in the cyclic-loaded condition. The surface of the specimens showed a slight orientation in the HDPE cyclic-loaded specimen as can be seem in b

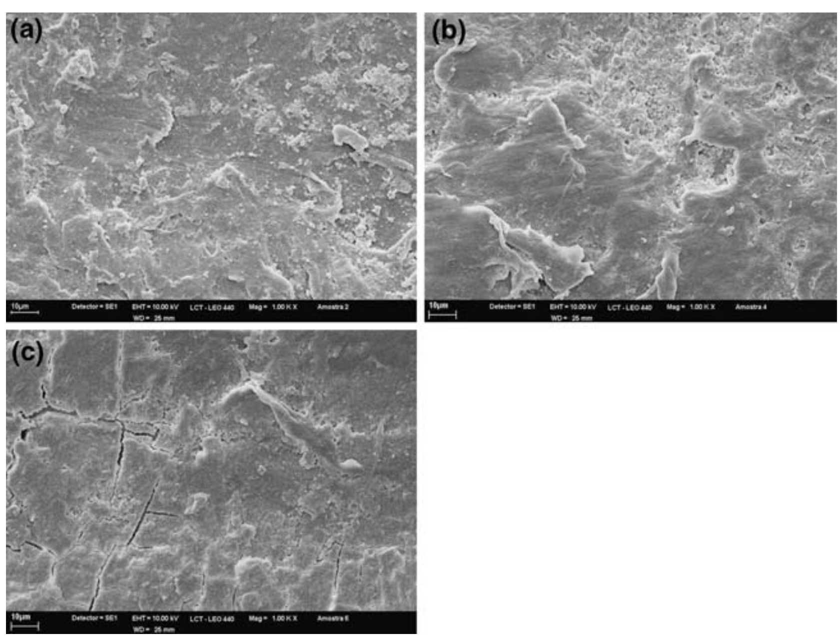
The appearance of the surface can change during weathering. More generally the change in the surface appearance may indicate the extent of degradation process [4]. The deterioration of the material caused by the cyclic loading, ultraviolet radiation and the seawater is clearly observed in the cyclic-loaded sample, exposed to ultraviolet radiation and seawater simultaneously, as can be seen in Fig. 8c. A type of pore and superficial flaws confirm the degrading effect of this environment factors in HDPE used in umbilical cables.

Conclusions

The results of this work made it possible to draw the following conclusions:

1. The tensile tests were important to determine the degrading effects in the external polymeric layer of the umbilical cable mainly after cyclic loading tests. The combination of ultraviolet radiation and seawater caused an increase of degradation in the polyethylene in the as-received condition, which was also verified during tensile tests.
2. The hardness measurements did not show a significant difference among the results obtained.
3. The effect of the cyclic loading combined with the effects of the two environment agents mentioned, i.e., ultraviolet radiation and seawater caused the major damage evaluated. The tensile tests were complemented with scanning electron microscopy (SEM) to verify the damage on the HDPE surface. A type of pore and superficial flaws, which appeared on the

Fig. 8 Scanning electron microscopy of the surface of HDPE in the cyclic-loaded condition: (**a**) aged under ultraviolet radiation; (**b**) aged inside artificial seawater; (**c**), aged under ultraviolet radiation and inside artificial seawater simultaneously. The deterioration of the material caused by the cyclic loading, ultraviolet radiation and the seawater is easily observed especially in the cyclic-loaded specimen, exposed to ultraviolet radiation and seawater simultaneously



HDPE surface, confirm the degrading effect of cyclic loading, ultraviolet radiation and seawater in umbilical cables. Therefore, the degradation can be accelerated by these environment factors, although the most important factor in the degradation process seems to be the damage cause by cyclic loading.

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