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Mechanical Performance of Bentonite Plugs in Abandonment Operations of Petroleum Wells

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Abstract: This study aims to evaluate how the operational procedure adopted for pellet placement and the exposure to subsurface conditions influence the mechanical integrity of bentonite plugs used as barrier elements in the abandonment of petroleum wells. To this end, the plugs were formed by hydrating the pellets directly in water, simulating the onshore procedure, while the offshore plugs were obtained from pellets hydrated in deionized water after immersion in diesel or olefin, which are suggested as displacement fluids. The plugs obtained were tested by compression and adhesion tests. These mechanical tests were also carried out for specimens obtained from plugs exposed to four formulations of synthetic formation waters. The results obtained demonstrated that, in the offshore procedure, the previous contact with olefin may adversely affects the mechanical stability of bentonite plugs, while plugs formed from pellets immersed in diesel presented satisfactory mechanical properties. However, the contact with formation water evidenced that the onshore plug presents superior resistance than the offshore plug previously immersed in diesel. The highly successful performance of the onshore plug was attested by the maintenance of the compressive strength, which exhibited a maximum reduction of 13%, even after exposure to the most saline formation waters.

Keywords: decommissioning; abandonment; sealing material; bentonite pellets; displacement fluids; formation water

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1. Introduction

A fundamental structural change is occurring worldwide in the energy sector with the transition from fossil fuel to renewable energy. As a result, many oil and gas structures will reach the end of their productive life in the next decades and need to be decommissioned [1]. In addition to the closure of operations, some other reasons can also lead to the need for the decommissioning of production systems, such as unprofitable production and environmental regulations and it has social, economic, and environmental implications [2–4].

Well abandonment is one of the main decommissioning operations and is planned for all oil and gas wells, whether exploratory, producing or injecting. It aims to maintain safe conditions, without the flow of fluids in the well to the seabed, in addition to avoiding contamination of aquifers [5,6]. To achieve this, it is necessary to restore perfect isolation between the different permeable intervals of the oil and/or gas zones through safety barrier elements [7].

Traditionally, abandonment is performed through a cementing process, which aims to create a barrier to seal the wellbore [7,8]. Although the cement barrier is considered effective in terms of the requirements of regulatory bodies, it may present some limitations and high costs [9,10]. Thus, the search for more efficient and economical solutions, in addition to the concern for environmental preservation and operational safety, boosted the development of new technologies in the petroleum industry [11,12]. In this context, one of the suggested alternatives to the use of cement plugs consists of the use of bentonite clay in its compacted form, which, due to its high swelling capacity and low permeability, has also been widely used in plugging seismic wells, water wells and nuclear waste deposits [9,13–15].

While cement has limitations related to contraction and mechanical or chemical degradation, resulting in lower integrity and high costs for repairing the plug, bentonite seals the formation more safely and reliably and ensures the integrity of the plug formed even after the formation of cracks, due to its greater plasticity [7,9,16]. Laboratory tests have also shown that hydrated bentonite is capable of restructuring itself even after failure [17].

Although the technical effectiveness of bentonite plugs is recognized, to the best of our knowledge, the published research considers mostly the hydro-mechanical behavior of plugs formed through conventional hydration [18,19]. As a result, the impact of the circumstances related to operational procedures and exposure to field conditions during application in petroleum wells on its mechanical integrity is not investigated.

In terms of operational procedures, the plug may present differences in physical conformation and chemical interactions on onshore and offshore wells, since the offshore procedure requires contact with a fluid to displace the pellets, prior to hydration [20,21]. Furthermore, subsurface conditions, especially the exposure to formation waters that saturate the reservoir significantly in mature wells, and generally present a high electrolyte content [22–24], may also impact mechanical properties. In this context, this study aims to evaluate how the operational procedure adopted for pellet placement and exposure to subsurface conditions influences the mechanical integrity of bentonite plugs used as barrier elements in the abandonment of petroleum wells.

2. Materials and Methods

2.1. Materials

The plugs were formed by pellets, consisting of the compacted form of bentonite, commercialized as Compactolit by Bentonit União Nordeste—BUN (Boa vista/Brazil).

Pellet hydration was carried out in deionized water and, exclusively for plugs prepared by the operational procedure adopted in offshore wells, the pellets were exposed to contact with organic fluids (diesel or olefin) before hydration.

After hydration, the bentonite plugs were immersed in four synthetic formation waters (FW1, FW2, FW3, FW4) with compositions based on formulations of formation water from Brazilian wells, presented in Table 1.

Table 1. Composition of formation waters.

	FW1	FW2	FW3	FW4
Chemical Compound	**Concentration (mg/L)**	**Concentration (mg/L)**	**Concentration (mg/L)**	**Concentration (mg/L)**
NaCl	31,001.00	158,176.75	116,391.32	32,945.00
$CaCl_2$	1603.70	2693.34	0	1009.00
$NaHCO_3$	6590.00	436.44	996.79	4806.35
$MgCl_2$	1478.89	0	0	1112.75
MgO	60.06	829.22	575.54	0
$Ca(OH)_2$	0	43.02	959.44	0
HCl	0	25.00	62.00	0
KCl	1359.00	3622.63	3769.45	1940.96
NaOH	0	0	851.37	0
$CaCO_3$	0	0	0	780.70

To prepare the formation waters, each component was added to a beaker containing 1 L of deionized water, under constant stirring in a magnetic stirrer, following the order of addition of the substance from the highest to the lowest proportion. After adding all components, the sample remained under stirring for 24 h.

2.2. Methods

2.2.1. Plugs Preparation

- Offshore Plugs

To obtain plugs using a methodology that fits the operational procedure proposed for offshore wells by Costa et al. (2023) [21], bentonite pellets were initially immersed in diesel or olefin for 60 min. This stage corresponds, under field conditions, to the operational mechanism of displacing the pellets through flow lines until they reach the location designed to establish the barrier inside the well, after swelling. After immersion, the pellets were briefly filtered through a 60 × 325 mesh stainless steel screen, and were hydrated inside metal molds for 24 h, in a volumetric ratio of 2:3 pellet/deionized water.

- Onshore Plugs

The methodology used for preparing the plugs simulating the operational conditions of onshore wells followed the same procedures proposed for hydrating the pellets presented previously, excluding only the prior contact with organic fluids, since in onshore wells the pellets are launched straight inside the well and, therefore, there is no need for the usage of a displacement fluid.

2.2.2. Mechanical Tests

The plugs obtained were manually cut into sections with approximate dimensions of 35 mm in diameter and 15 mm in height to carry out the mechanical tests. The procedures used for the mechanical tests are the following:

- Compressive Strength

In order to ensure that the plug has the appropriate mechanical properties to withstand the loads to which it will be subjected, it is essential to evaluate its compressive strength. For this, tests were carried out on the Haake Mars 60 rheometer Thermo Scientific (Karlsruhe, Germany), using the 35 mm parallel plate geometry set (P35/Ti).

During the tests, an axial ramp was programmed to monitor the height variation (Δh) between the rotor and the sample for around 2 min, until full compression was reached. Compressive strength was then determined by the maximum force recorded at the moment of rupture of the specimen, representing the maximum normal force applied during the test. All collected data were processed using RheoWin Data Manager software version 4.86.0002.

- Adhesion

The adhesion of the barrier element to the casings and formations is considered a key factor in ensuring its proper location in the well, making it essential to understand its adhesive behavior. For this, the adhesion strength was evaluated through tests conducted on the Haake Mars 60 rheometer Thermo Scientific (Karlsruhe, Germany), using the 35 mm parallel plate geometry set (P35/Ti).

During the tests, an axial ramp was programmed to gradually increase the height difference (Δh) between the rotor and the test specimen, at a speed of 0.1 mm/s. The maximum adhesion force was then recorded when the sample completely detached from the plate, representing the adhesion overtime during this process. All collected data were processed using RheoWin Data Manager software.

2.2.3. Plugs Interaction with Formation Waters

Mechanical tests were also carried out for specimens obtained from plugs that were exposed to contact with formation waters at the end of the hydration time. To this end, the plugs obtained, still inside the molds, without their base cap, were immersed in beakers containing 50 mL of each of the four synthetic formation waters for 60 min. After this time, the plugs were demolded and cut to obtain the test specimens. The remaining volume of water in the beaker was measured to calculate the water absorption by each plug.

3. Results and Discussion

3.1. Aspect and Mechanical Properties of Offshore and Onshore Plugs

As shown in Figure 1, the plugs formed according to the methodology proposed for offshore wells presented very different physical aspects in terms of the type of organic fluid used before hydration. The plug formed by pellets previously immersed in diesel presented a firm and cohesive appearance, while the plugs formed by pellets previously immersed in olefin, showed high fragility and fragmented during demolding.

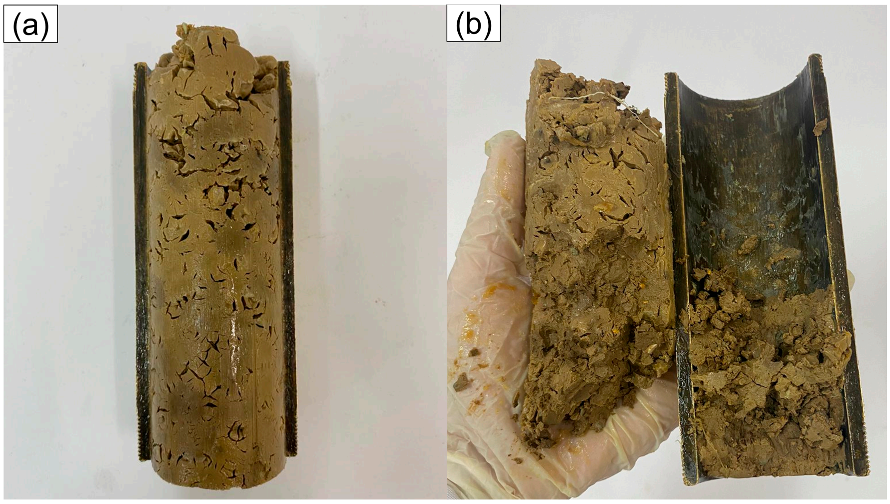

Figure 1. Aspect of the plug formed by pellets previously immersed in diesel (**a**) and olefin (**b**), following the methodology proposed for offshore wells.

The fragility of the plug obtained with pellets previously immersed in olefin is probably due to the lower cohesion after hydration in water. It can be better investigated based on contact angle tests, which indicate that bentonite clay is wettable by olefin [25]. As a result, olefin tends to adsorb around the clay particles, forming an oily film that prevents its adequate hydration. This behavior is further strengthened by the viscosity of the oil phase [26]. Therefore, since olefin is more viscous than diesel, it is more easily adsorbed by the bentonite pellets, reducing the cohesion of the particles after hydration.

Thus, although olefin and diesel have demonstrated satisfactory results based on the swelling potential of bentonite pellets in water after the previous contact with these fluids [21], the fragility presented by the plug previously immersed in olefin shows that the choice of the appropriate fluid used for the displacement stage in an abandonment operation of an offshore wells must necessarily consider the physical aspect and mechanical properties of the plug obtained after swelling.

The plug formed from direct hydration of pellets in water, following the methodology compatible with the onshore operational procedure is shown in Figure 2. It also presents a firm and cohesive physical appearance.

The graphs presented in Figure 3 show the results of compressive strength (expressed in terms of force as a function of the height of the specimen) and adhesion for the plug formed by pellets previously immersed in diesel, identified as "offshore plug", and for the plug formed without contact with organic fluids, identified as "onshore plug".

Figure 2. Aspect of the plug formed by pellets hydrated directly in water, following the methodology proposed for onshore wells.

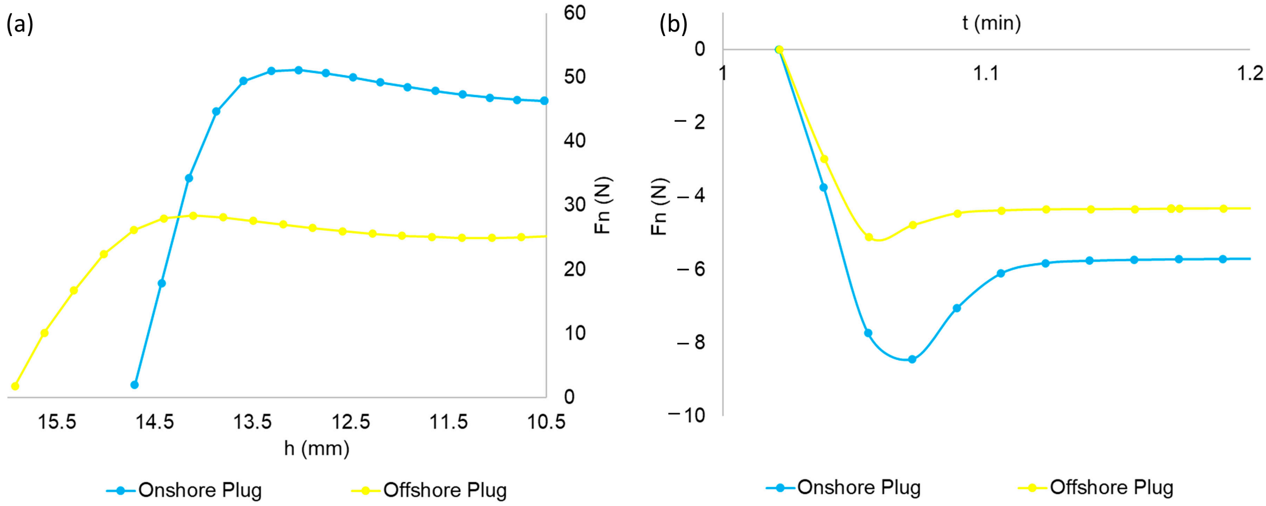

Figure 3. Compressive strength (**a**) and adhesion (**b**) for plugs obtained from the proposed methodology for offshore and onshore wells.

Although there are no technical standards and regulations that specify the requirements for mechanical properties of bentonite plugs, it is worth highlighting that the use of these elements in onshore wells, addressed in this study, has reached level 8 of the TRL scale (Technology Readiness Level), and its application is already completed and qualified through testing. It attests that the mechanical properties presented by the onshore plug can be considered as a comparison parameter for the other plugs analyzed.

According to the analysis of Figure 3a, it was observed that the onshore plug presented a higher compressive strength, recording a maximum force at the moment of specimen rupture of 51.1 N, while the offshore plug presented an average force of 28.4 N, which represents a reduction of around 44%. A similar behavior was observed for the adhesion force, presented in the graph in Figure 3b, for which a reduction of 38% is observed for the offshore plug, concerning the onshore plug.

The reduction in compression resistance for the offshore plug may be related to the adverse effects of diesel on the hydration of pellets since it is hydrophobic and may prevent the interaction of bentonite particles with water molecules [27].

Similarly, the reduction observed for adhesion tests is also influenced by the prevention of water adsorption resulting from the previous interaction of bentonite particles with non-polar fluids, which compromises the hydration and attenuates the cohesion of the plug, causing a greater propensity for detachment. Furthermore, the lubricating effect of diesel can cause a sliding and slipping effect between the bentonite particles, reducing the friction angle and, therefore, minimizing adhesion [27].

Although the onshore plug presented higher compression resistance and adhesion, the mechanical properties obtained for the offshore plug must be considered in the design of well abandonment operations, since the loads to be supported, and the surfaces (casings or formations) to which the barrier must adhere, are particular for each well.

3.2. Aspect and Mechanical Properties of Plugs after Interaction with Formation Waters

The interaction tests with formation waters have also used only offshore (diesel) and onshore plugs, given the low cohesion and integrity of plugs formed from pellets previously immersed in olefin (Figure 1). However, it was found that the plugs formed by pellets immersed in diesel presented low resistance to the formation waters, since after contact with any of the four formulations, they easily fragmented, as shown in Figure 4.

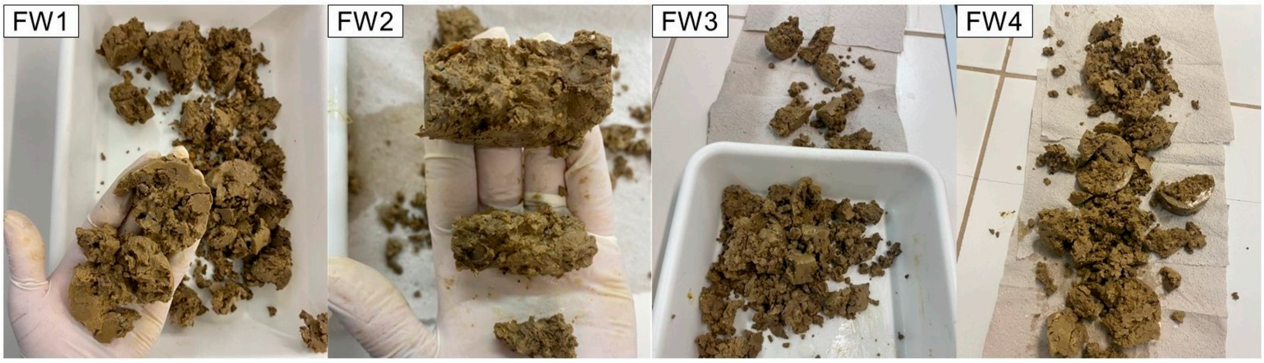

Figure 4. Offshore plugs (diesel) after contact with synthetic formation waters.

As the offshore plugs presented low integrity after contact with formation waters, only the plugs obtained from the methodology proposed for onshore wells were used to carry out the mechanical tests. The visual appearance of the base of the onshore plugs and each formation water, before and after immersion is shown in Figures 5 and 6, respectively.

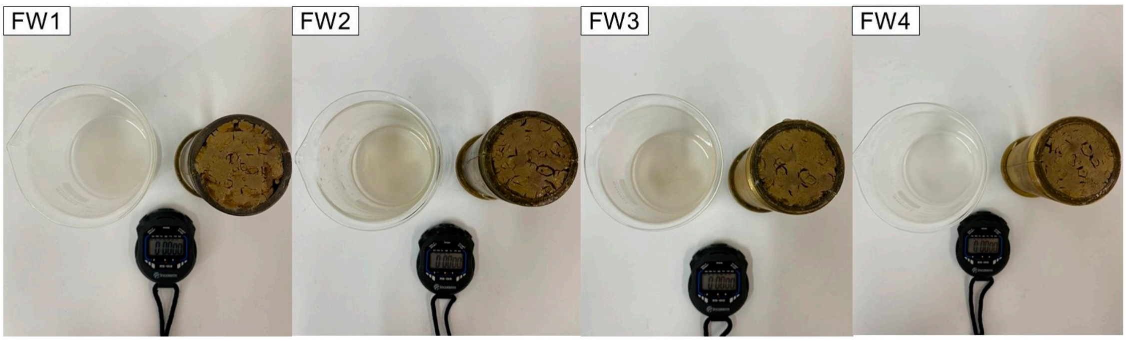

Figure 5. Formation waters and base of the plugs onshore before immersion.

The formation waters that presented the higher salinities (FW2 and FW3) also presented a greater amount of clay particles. This behavior results from the disintegrating action of the ionic environment on the bentonite pellets, since montmorillonite mineral layers are easily infiltrated by cations and this results in a volume increase [28]. These layers may expand until they break, resulting in the loss of their initial cohesion and disintegration into smaller particles. This process is accelerated by the high concentration of electrolytes of the more saline formation waters, which increases the speed of expansion and disintegration of the pellet [23,29].

Figure 7 shows that, despite the presence of particles in the formation water, the integrity of the plugs was maintained, and they present a similar appearance to the onshore plug in its initial state.

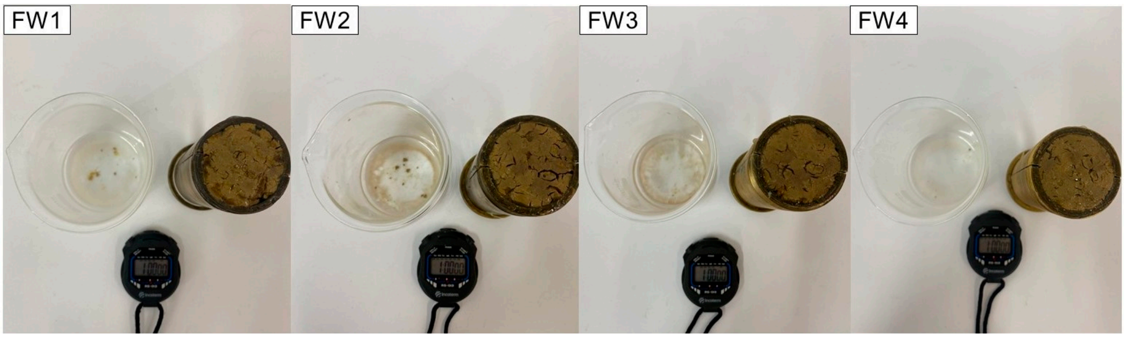

Figure 6. Formation waters and base of the plugs onshore after immersion.

Figure 7. Appearance of onshore plugs after immersion in each formation water.

The maintenance of the physical aspect of the onshore plug, even after contact with the formation waters, is justified by the significant interaction between the particles after hydration, which results in a greater cohesion. This behavior attests that the proportion of water and the methodology used for the hydration of the pellets was adequate.

After contact with the synthetic formation waters, the plugs have shown an increase in the opening between the metal mold plates (Figure 8). This behavior demonstrates that there was absorption of formation water during immersion and attests that the infiltration of electrolytes causes an increase in the volume of the clay mineral montmorillonite [28]. The volume of each formation water absorbed is shown in Table 2.

Figure 8. Opening between the plates of the metal mold due to the swelling of the plug immersed in FW3.

Table 2. Absorbed volume of synthetic formation waters by the onshore plug.

Formation Water	FW1	FW2	FW3	FW4
Absorbed Volume (mL)	3.5	4.5	4.0	3.5

As shown in Table 2, the volume absorbed by the plugs immersed in more saline waters (FW2 and FW3) was slightly greater.

The mechanical properties presented by the onshore plug after contact with the formation waters are shown in Figure 9.

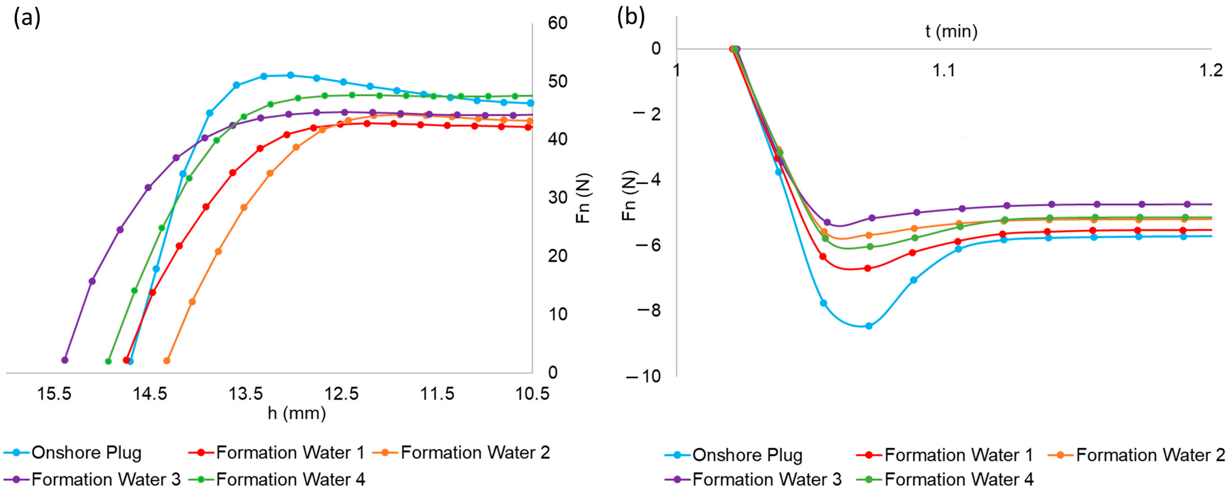

Figure 9. Compressive strength (**a**) and adhesion (**b**) for the onshore plug before and after immersion in formation waters.

The compressive strength for each specimen, presented in Table 3, was obtained from the results presented in the graph in Figure 9a.

Table 3. Average compressive strength of the specimens obtained from the onshore plug before and after contact with the formation waters.

	Onshore Plug	Formation Water 1	Formation Water 2	Formation Water 3	Formation Water 4
Compressive strength (N)	51.1	42.9	44.6	44.8	47.5

As shown in Figure 9a and according to the data in Table 3, the bentonite plugs showed a reduction in compressive strength after immersion in the formation waters. However, even the largest reductions, which are in the order of 13%, observed for the most saline formulations (FW2 and FW3), were not very significant. This behavior highlights the high resistance of the onshore plug to formation fluids.

The reduction in compressive strength upon contact with formation waters can be attributed to the reduction in expansion and expansion pressure on a macro scale [30], which can compromise the physical integrity of the plug [23,31]. In this way, the salinity of the formation water can adversely affect the resistance of the plug.

The adhesion of plugs in contact with synthetic formation waters was also affected by the presence of electrolytes (Figure 9b). The adhesion of the plugs in contact with more saline waters (FW2 and FW3) was approximately 33% and 37% lower, respectively, than that for the onshore plug, while the adhesion of the plugs in contact with the lowest saline waters (FW1 and FW4) was approximately 20% and 28% lower, respectively. These results reinforce the correlation between the salinity of the formation water and the mechanical properties of the plug; however, for the adhesion tests the reduction observed is more significant than for the compressive strength.

The parameters that determine clay resistance are complex and influenced by a series of electrical and chemical interactions between the particles [32], as well as the contact stress interparticle. When particles are close together, the contact stress increases, resulting in a denser and more resistant plug. Therefore, it is important to consider the effect of external tensions which can cause variations in the space between particles and in their orientation, resulting in an imbalance in the electrical forces [33].

In deep wells, the in situ condition may improve the mechanical stability of the plugs, as observed previously, when comparing the mechanical properties of bentonite plugs on laboratory and large-scale tests [34]. Thus, it is expected that the loss of integrity presented by offshore plugs and the reduction in the mechanical properties of the onshore plug, observed after the contact with formation waters in laboratory tests, will be much less pronounced under field conditions, ensuring the successful performance of these elements in well abandonment, regardless of the operational procedure used for their placement.

4. Conclusions

In this work, a series of experiments were carried out to evaluate how the operational procedure adopted for pellet placement and exposure to subsurface conditions influences the mechanical integrity of bentonite plugs used as barrier elements in the abandonment of petroleum wells. The following conclusions can be drawn from the results:

- Prior analysis of the mechanical properties of the plug is a determining factor in the appropriate choice of the operational procedure and, in the case of offshore wells, of the type of displacement fluid used to dispose the pellets inside the well in the design of abandonment operations.
- Contact with organic fluids used to displace the pellets in offshore wells reduces the mechanical properties of bentonite plugs; however, this reduction compromises significantly only the stability of plugs formed by pellets previously immersed in olefin. Consequently, plugs formed by pellets previously immersed in diesel are promising alternatives for offshore abandonment operations.
- The onshore plug presents satisfactory mechanical resistance to contact with formation waters, so that the plug's capacity to support loads, represented by compressive strength, presents a maximum reduction of 13% after exposure to this condition, although the adhesion property presents more pronounced reductions.
- The salinity of the formation water has a significant influence on the mechanical properties of the bentonite plug, adversely affecting these parameters, especially the adhesion properties.

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