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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 the pellets placement and the exposure to subsurface conditions influences the mechanical integrity of bentonite plugs used as barrier elements in the abandonment of petroleum wells. To this end, two methodologies were used to obtain the plugs: from the first methodology, the pellets were immersed in diesel or olefin, which are proposed as displacement fluids in offshore operations, and then, hydrated in deionized water; in the second methodology, representative of onshore operations, the pellets were directly hydrated in deionized water. After that, the plugs were tested by compression and adhesion tests. These mechanical tests were also carried out for test specimens obtained from plugs exposed to four formulations of synthetic formation waters. The results obtained demonstrated that the previous contact with olefin adversely affects the mechanical stability of bentonite plugs, while plugs formed from pellets immersed in diesel presented satisfactory mechanical properties. The mechanical properties of onshore plugs attested the highly successful performance of these elements, once its compressive strength was minimally impacted by exposure to formation waters and more pronounced reductions were observed only in the adhesion properties after the contact with higher salinity formation waters.

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

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 the productive life in the next decades and need to be decommissioned [1]. Besides closure of operations, some other reasons can also lead to the need of the decommissioning of production systems, such as unprofitable production and environmental regulations and it has social, economic and environmental implications [2–4].

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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 into 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, the 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, besides the concern towards 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 in 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 in a safer and more reliable way and guarantees the integrity of the plug formed even after the formation of cracks, due to their greater plasticity [7,9,16]. Laboratory tests have also showed that hydrated bentonite is capable of restructuring itself even after failure [17].

Although the technical effectiveness of bentonite plugs is recognized [18,19], there are still gaps regarding their application in oil wells as a barrier element in abandonment operations, especially in terms of mechanical integrity. In this context, it is necessary to consider the influence of the operational procedures adopted on the pellets placement inside the well [20], which can expose the material to different conditions in onshore and offshore environment [21], influencing the chemical interactions that occurs during hydration and/or the physical conformation of the plug. Furthermore, subsurface conditions may also impact mechanical properties, and are mainly related to the contact of the plug with the formation waters that saturate the reservoir significantly in mature wells, and generally presents a high electrolyte content [22–24]. In this context, this study aims to evaluate how the operational procedure adopted for the pellets placement and the 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, which consist in the compacted form of bentonite, comercialized as Compactolit (Bentonit União Nordeste – BUN/ Brazil).

Pellet hydration was carried out in deionized water and, exclusively for plugs prepared in accordance with 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 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	31001,00	158176,75	116391,32	32945,00
CaCl2	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 1L 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 one. After adding all components, the sample remained under stirring for 24 hours.

2.2. Methods

2.2.1. Plugs Preparation

- Offshore Plugs

In order 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 minutes. 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 60x325 mesh stainless steel screen, and were hydrated inside metal molds for 24 hours, 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 straight launched inside the well and, therefore, no displacement fluids are needed.

2.2.2. Mechanical Tests

To carry out the mechanical tests, the plugs obtained were manually cut into sections with approximate dimensions of 35 mm in diameter and 15 mm in height. 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), 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 minutes, 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 this process. All collected data were processed using RheoWin Data Manager software.

- Adhesion

The adhesion of the barrier element to the casings and formations is considered a key factor in ensuring its permanence in the proper location into 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, 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 over time 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 which 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 50mL of each of the four synthetic formation waters for 60 minutes. 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.

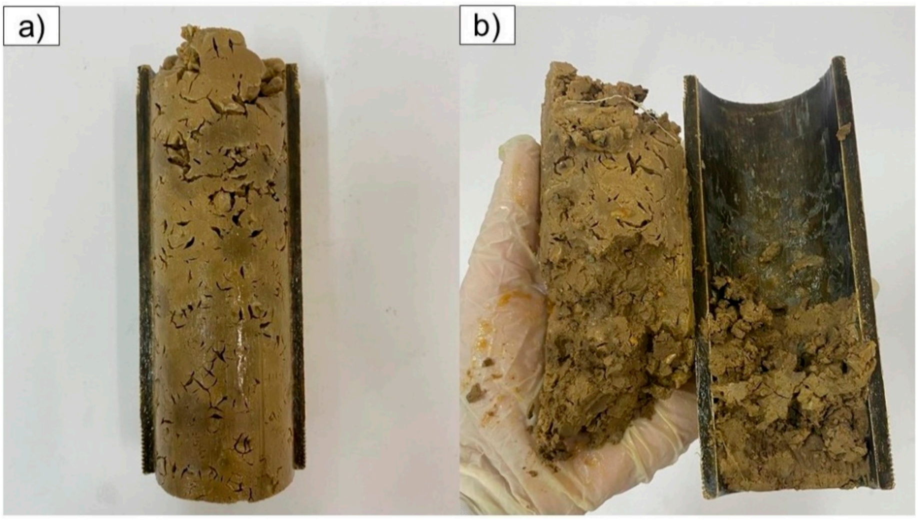

Figure 1. Aspect of the plug formed by pellets previously immersed in diesel (a) and olefin (b), following the methodology proposed for offshore wells.

The fragility of the plug obtained with pellets previously immersed in olefin is probably due to the lower cohesion after hydration in water, since bentonite clay is wettable by olefin, which results in its adsorption and formation of an oily film around the clay particles [25]. This behavior is further strengthened by the viscosity of the oil phase [26]. Therefore, since olefin is more viscous than diesel, the oily fraction of this organic fluid is more easily adsorbed by the material, reducing the cohesion of the particles after hydration.

Thus, although olefin and diesel have demonstrated satisfactory results in the displacement of bentonite pellets, based on the swelling potential of the 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 in this stage of the abandonment operation in offshore wells must necessarily consider the physical aspect and mechanical properties of the plug obtained after swelling.

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

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

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 one formed without contact with organic fluids, identified as “onshore plug”. These tests were not performed for the plug formed by pellets previously immersed in olefin due to its high fragility, which made it difficult to obtain test specimens.

Although the interpretation of the results of mechanical properties of bentonite plugs is limited by the absence of technical standards and regulations that specify the requirements for these parameters, 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, so that the mechanical properties presented by the onshore plug are considered as a comparison parameter for the other plugs analyzed.

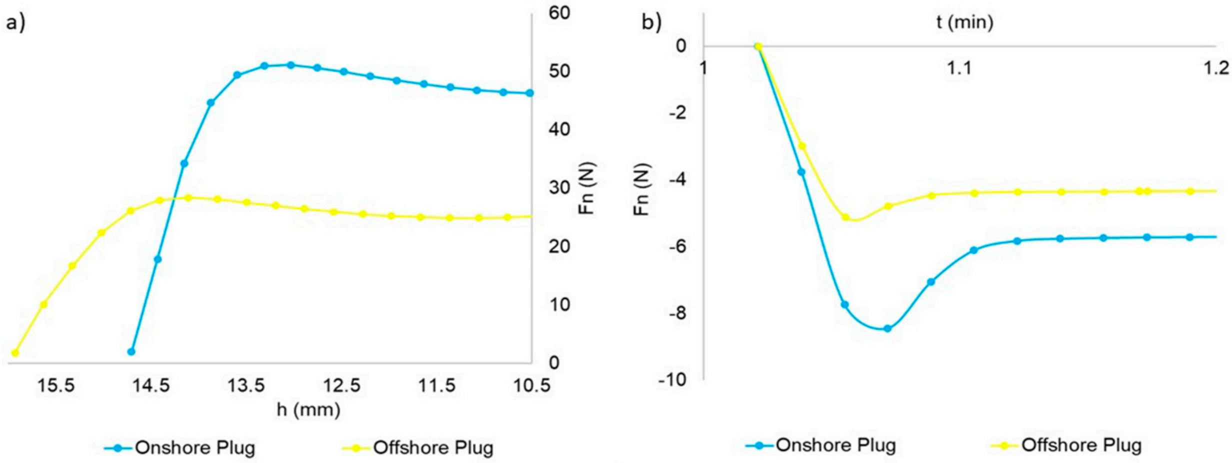

Figure 3. Compressive strength (a) and adhesion (b) for plugs obtained from the proposed methodology for offshore and onshore wells.

According to the analysis of Figure 3(a), it was observed that the onshore plug presented the highest compressive strength, recording a maximum force at the moment of specimen rupture of 51.1N. The offshore plug presented an average force of 28.4N, which represents a reduction around

44%. A similar behavior was observed for the adhesion results, presented in the graph in Figure 3(b), for which a reduction of 38% is observed for the offshore plug, in relation to the onshore plug.

The reduction in compression resistance for the offshore plug may be related to the adverse effects on the hydration of pellets, resulting from the methodology used to prepare the plug, since diesel, which is hydrophobic, prevents the interaction of bentonite particles with water molecules [27].

Regarding the reduction observed for adhesion tests, it is worth highlights that this mechanical property is governed by complex factors, including the force that holds the molecules together, which is called cohesion, and the force that keeps the molecules in contact with the substrate surface. For bentonite plugs, interaction with non-polar fluids, such as diesel, is capable of attenuating the cohesion of the material, resulting in 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, these results do not impair the application of the offshore plug as a barrier element in well abandonment, since the loads to be supported during the operation, and the surfaces (casings or formations) to which the barrier must adhere, are particular for each well. It must be considered when designing the operation, taking into account the operational procedure adopted for the pellets placement and its implications on mechanical properties.

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 present low resistance to the formation waters, since after contact with any of the four formulations, they easily fragmented, making it impossible to obtain the specimens to carry out the mechanical tests, as recorded in Figure 4. In this way, only the plugs obtained from the methodology proposed for onshore wells, with no prior immersion in organic fluids, presented satisfactory integrity even after contact with the formation waters, and made it possible to carry out the mechanical tests.

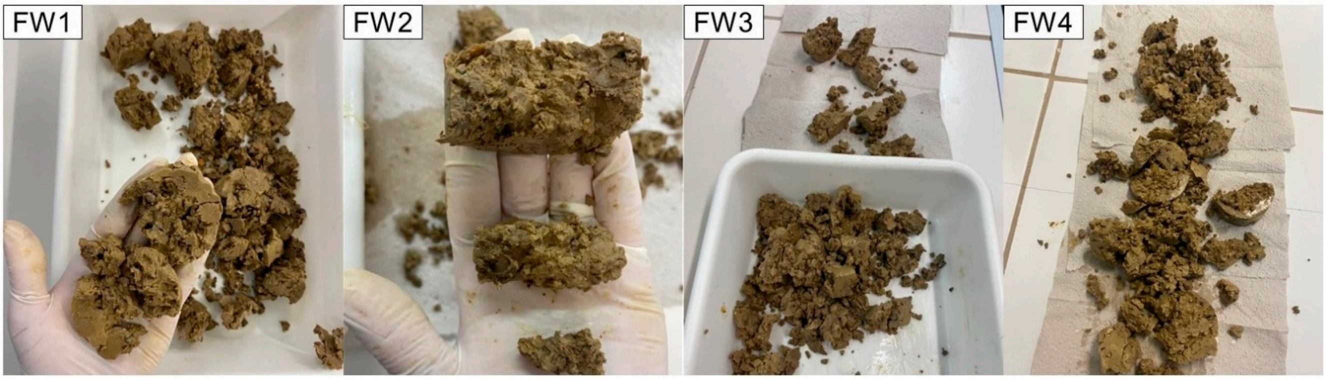

Figure 4. Offshore plugs (diesel) after the contact with synthetic formation waters.

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.

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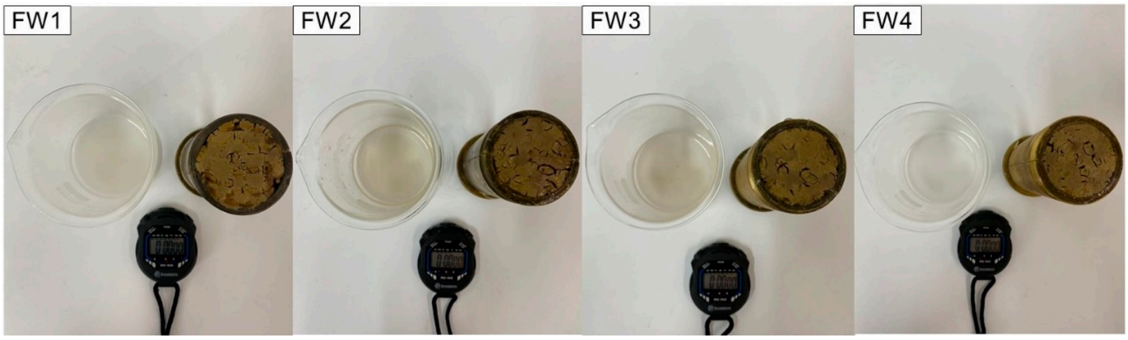

Figure 5. Formation waters and base of the plugs onshore before immersion.

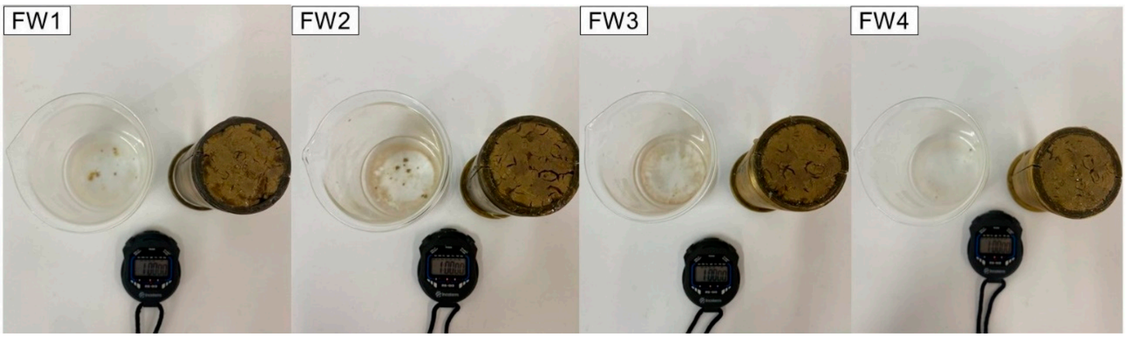

Figure 6. Formation waters and base of the plugs onshore after immersion.

The formation waters that presented the higher salinities (FW2 and FW3) presented also a greater amount of clay particles, while the samples with lower salinities (FW1 and FW4) presented a clearer appearance. This behavior results from the disintegrating action of the ionic environment to the bentonite pellets, since montmorillonite mineral layers are easily infiltrated by cations and it results in volume increasing [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 salinity of the formation water, which increases the speed of expansion and disintegration of the pellet. Thus, this degradation occurs more markedly for plugs immersed in waters with higher salinity [23,29].

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

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 greater cohesion. This behavior attests that the proportion of water and the methodology used for hydration of the pellets was adequate.

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

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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, all plugs absorbed part of the formation water during immersion. However, 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.

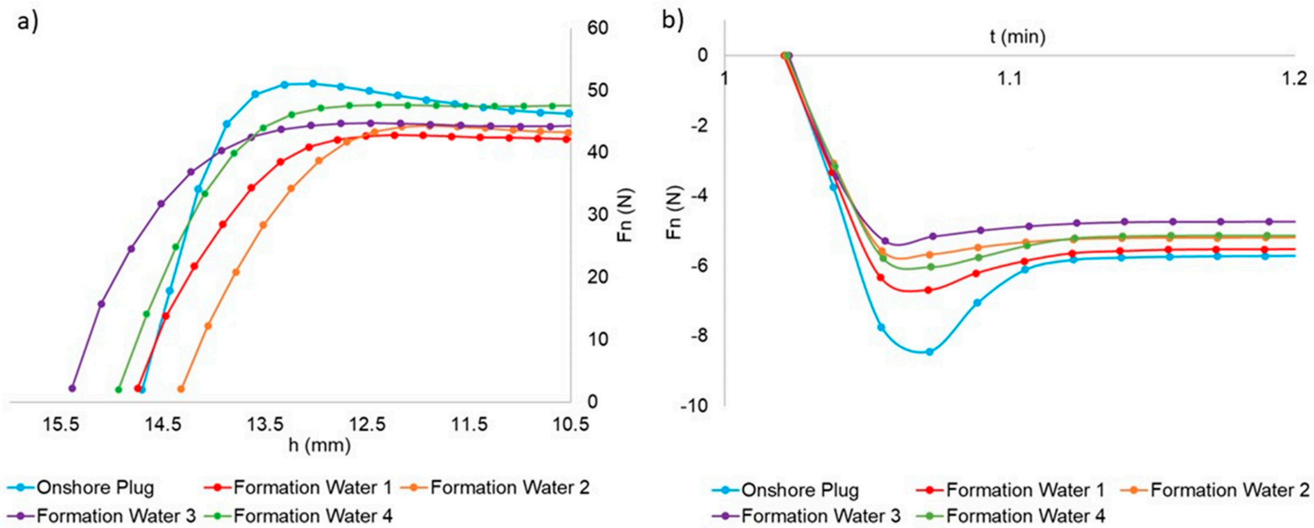

Figure 9. Compressive strength (a) and adhesion (b) for the onshore plug before and after immersion in formation waters.

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

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 9(a) 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 plug to formation fluids and the correlation of this mechanical property with the salinity of the fluid in the subsurface.

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.

Besides compressive strength, the adhesion of plugs in contact with synthetic formation waters was also affected by the presence of electrolytes (Figure 9(b)), so that plugs in contact with more saline waters presented reduction on this property. The adhesion of the plugs in contact with more saline waters (FW2 and FW3) was approximately 33% and 37% lower, respectively, in relation to the onshore plug, while the adhesion of the plugs in contact with the less 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, also observed in the compressive strength test, however, for the adhesion tests the reduction observed is more significant.

The parameters that determine clay resistance are complex and influenced by a series of electrical and chemical interactions between 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 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 the pellets placement and the 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 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, so that plugs formed by pellets previously immersed in diesel are promising alternatives for offshore wells abandonment;
- 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, is minimally affected by 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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