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An investigation into the Impact of Gaberoun Lake Water Quenchant on Microstructure and Hardness of AISI 1035 Carbon Steel

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ABSTRACT

This investigation aims to study the effect of Gaberoun lake water on the microstructure, impact energy and hardness of 1035 carbon steel. The applications of AISI 1035 include machinery parts where toughness and hardness are requisites. The cooling performance of Gaberoun lake water as a quenchant was evaluated against two other quenchants (Mediterranean seawater and Natural water). The results revealed that the hardness is maximised by the highest quenching severity, which produces a high-volume fraction of tempered martensite when Gaberoun lake water is used. The lowest quenching severity was observed when natural water was employed as the quenchant, resulting in a mixed microstructure containing a significant amount of the ductile ferrite phase. The study confirms the inverse relationship between hardness and toughness properties, emphasising the importance of selecting a heat treatment process that strikes a balance between the said properties for the intended applications.

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Keywords: *AISI 1035 carbon steel, Heat treatment, Quenchants, Gaberoun lake water, Mediterranean Sea water, Natural water, Microstructure, Hardness test.*

1. Introduction

Materials intended for building structures and elements of agricultural machinery should ensure not only aesthetic appearance, but also the safety of people and objects during use. AISI 1035 steel is one of the most popular non-alloy steels. It is often used in various types of constructions, also periodically exposed to a harsh working environment [1]. It contains from 0.31% to 0.38% carbon and, in small amounts, of silicon, manganese, sulphur and phosphorus as shown in Table 1. The mechanical, physical and chemical properties of AISI 1035 carbon steel, including corrosion resistance, are affected by its chemical elements and different heat treatment conditions. Due to its low cost and high efficiency, AISI 1035 medium carbon steel is widely used in agriculture, construction and engineering for structural components. It's mainly used in the form of bars and sections in steel structures, as well as in the production of various machine parts, such as shafts, cylinders, gear wheels, axles, discs, traverses, etc. The development of corrosion-resistant steels resulted in the gradual displacement of carbon steels from application in structures operating in an aggressive environment [2].

Today, the heat treatment process is widely used to achieve high mechanical properties. The major requirements of medium carbon steel are high yield strength, high proportional limit, and high fatigue strength. These desirable properties of medium carbon steel can be achieved by adding suitable alloying elements and by heat treatment. Heat treatment operation is a means of controlled heating and cooling of materials to effect changes in their mechanical properties. Heat treatment is also used to increase the strength of materials by altering certain manufacturability objectives, especially after the materials might have undergone major stresses like forging and welding [3]. However, it was known that the mechanical properties of steel were strongly connected to its microstructure obtained after heat treatments, which are performed to achieve good hardness and tensile strength with sufficient ductility. [4]. The material modification process modifies the behaviour of the steels beneficially to maximise service life (i.e. stress relieving) or increase strength properties (e.g. cryogenic treatment) or add some other desirable properties. The Heat treatment generally is classified into (i) Thermal treatment, which consists of softening process: Annealing and normalising, hardening process: Hardening and Tempering; (ii) Thermochemical Process, which

consist of carburising, nitriding, and Boronising; (iii) Thermomechanical Processes, which consist of mechanical working operation during the heat treatment cycle [5,6]. Though heat treatment is not a new area, it has not been put into effective use because most of the researchers look at the process in general. It has not been localised for an improvement/modification on getting the required results from these steel materials that are abundant in our daily life, especially where most of the steel products are from recycled scrap materials. Water quenching in steels is a rapid cooling process used to harden steel after it's been heated to the austenitizing temperature [7]. It's common in heat-treating carbon and alloy steels when a very fast cooling rate is needed, and a maximum hardness is the priority. However, cracking, distortion/warping, and quench shock are the most common drawbacks of the water quenching process if the heat treatment process is performed improperly. Water quenching is typically used for medium to high carbon steels (0.3 - 0.8 % C). Different water and water-based solutions are used in quenching processes, such as natural water, brine or salt water, caustic (Alkaline) and aqueous polymer solutions. It was revealed that quenching media have a significant effect on the cooling speed during the quenching process [8].

2. Systematic Literature Review

Several studies have been conducted to investigate the effects of quenchants, particularly water-based quenchants such as natural or tap water, brine or salt water and others on the mechanical properties of materials. For instance, an experimental study by Apichai [9] investigated the effects of different quenchants (water and brine or salt water) in the hardening process on microstructures and mechanical properties of alloy steel grade AISI 5160. The results show that the quenched samples in water after hardening at 810°C for 30 min brought the best combination of mechanical properties as compared with salt water quenched media. Another work by Ejiko et. al. [10] examined the impact of different quenchants (water and oils) on the hardness and impact energy of mild carbon steel. The findings reveal that the sample quenched in oils exhibited the highest value of 64.32 J, showing its ability to absorb a significant amount of energy before fracture, while the water-quenched sample had the lowest impact energy value of 57.94 J. On the other hand, the quenched sample has exhibited the highest hardness value of 78.2 HBN compared with oils quenched samples. Another investigation was performed where three samples of AISI 1090 carbon steel were furnace heated at a temperature of

900°C in a crucible furnace and quenched using salt water, natural water and oil to harden the steel samples [11]. Results show that natural water achieved the highest hardness value of 250 HB compared with other quenched samples. Adeyi et. al. [12] compared the quenching performance of three different quenchants in terms of hardness and material removal rate (MRR) when turning heat-treated mild carbon steel. The samples quenched in water cooled with a cooling rate of 2.58° C/s achieved the highest hardness value of 309.23 BHN compared to other quenchants. However, water-quenched samples produced the lowest MRR of 0.01 mm^3/min. It was concluded that the type of quenching media used during heat treatment could alter (optimise or reduce) the machinability of the steel being heat treated. Nwigwe et. al. [13] assessed the influence of natural and salt water quenchants on the hardness of medium carbon steel. The findings reveal that the samples quenched in salt water exhibited the highest hardness value of 40 HRC compared to natural water quenched samples (37 HRC) after a 3hr soaking time. This result somehow contradicts the findings of [9,11], where natural water achieved the highest values of hardness compared to salt water. It was concluded that the soaking time affects the machinability of the steel being heat treated.

Current literature indicates that researchers and manufacturers remain motivated to investigate alternative water-based quenchants to improve the mechanical properties of materials like steel, especially when these quenchants are efficient, affordable, and locally available. Nevertheless, the potential of unique local water resources as sustainable quenchants has not yet been fully explored. Thus, this work compares the effect of a local lake water quenchant (Gaberaoun Lake Water) against natural water and Mediterranean Seawater quenchants on the microstructure and hardness of heat-treated AISI 1035 carbon steel. Additionally, the influence of these quenchants on the impact energy of the tested samples is examined.

3. Experimental work

The material investigated in this study was AISI 1035 medium carbon steel alloy, which was supplied locally in the form of bars with Ø 13 mm diameter and 1500 mm length. Table 1 shows the chemical composition of the supplied AISI 1035 medium carbon steel. Three different water quenchants were used in this study; natural water, Mediterranean Seawater and lake water which was supplied locally from

Gaberoun lake located in the southwest of Libya (Fazan district). Tables 2, 3 and 4 illustrate the chemical analysis of all water quenchants used in the research.

Table 1. Chemical composition of the supplied AISI 1035 carbon steel alloy [2]

Weight (%)	Iron, Fe (%)	C (%)	Si (%)	Mn (%)	P (%)	S (%)
Min	98.63	0.31	0.254	0.6	≤ 0.040	≤ 0.050
Max	99.09	0.38	0.35	0.9		

Table 2. Chemical analysis of Gaberaoun lake water (mg/l)

Weight (%)	PH	Cl^-	TDS	SiO_3	NO_3	PO^{-3}_4
Min	9.45	70.27	90.60	3.46	316.70	17.83
Max	10.31	70.19	115.30	6.91	408.30	72

Table 3. Chemical analysis of mediterranean seawater (mg/l) [14]

Weight (%)	PH	Cl^-	Na^+	Ca^{+2}	K^+	SO^{-2}_4
Min	8.03	18.980	10.556	4.00	3.80	2.649
Max	8.63	22.100	12.500	4.50	4.50	3.14

Table 4. Chemical analysis of natural water (mg/l) [15]

Weight (%)	PH	Cl^-	Na^+	Ca^{+2}	K^+	SO^{-2}_4
Min	6.5	18	19	4.00	0.8	10.7
Max	7.5	20	26	4.60	3	13

Nine similar samples of AISI 1035 alloy with Ø 13 mm in diameter and 10 mm length were cut equally and subjected to the following heat treatments using a Gallenkamp laboratory electrical furnace, as shown in Figure 1. The Gallenkamp laboratory electrical furnace is a highly reliable, high-temperature heating device widely used in scientific laboratories for applications such as ashing, heat treatment, materials testing, and component ignition. The furnace has a temperature range of up to 1,200°C and a power rating of up to 12 kW at 220/240V.



Figure 1: Image of the lab scale Gallenkamp electrical furnace used in the study

4. Heat treatment and quench hardening

The nine samples were loaded into the furnace and heated to the austenite phase field at 950˚C for 30 min soaking time. Every three samples were then quenched using three different water quenchants, which were Gaberoun lake water, Mediterranean Seawater and natural water. Further, all quenched samples were subjected to a tempering treatment at 600˚C and soaked for 30 min.

5. Microstructure evolution of AISI 1035 during heat treatment

Prior to microstructural analysis, all samples endured standard metallographic preparation, including mounting, grinding, polishing, and etching with a suitable reagent (e.g., 2% Nital) to reveal the grain boundaries and phases. The microstructural analysis was conducted using a digital optical microscope at a different magnification zoom (200x and 210x). Figure 2 shows all the equipment used for sample preparation for the metallographic microstructure test. The heat treatment process, austenitizing at 950°C for 30 min soaking time, followed by quenching and subsequent tempering at 600°C for 30 min resulted in significant microstructural transformation from the initial ferrite and pearlite structure. The high cooling rate during quenching transformed the austenite into a hard, non-equilibrium phase, primarily **lath martensite**, which was then tempered to improve ductility and toughness. The final microstructure is expected to consist of **tempered**

martensite and potentially some transformation products like **bainite** or **ferrite**, depending on the cooling severity of the different quenchants.



Figure 2 : Equipment used for sample preparation for metallographic microstructure test

5.1 Microstructures analysis of Gaberoun lake water quenched samples

Figure 3 (a, b, c, d) presents the optical micrographs of the AISI 1035 steel sample quenched in Gaberoun lake water and subsequently tempered at 600°C for 30 min.

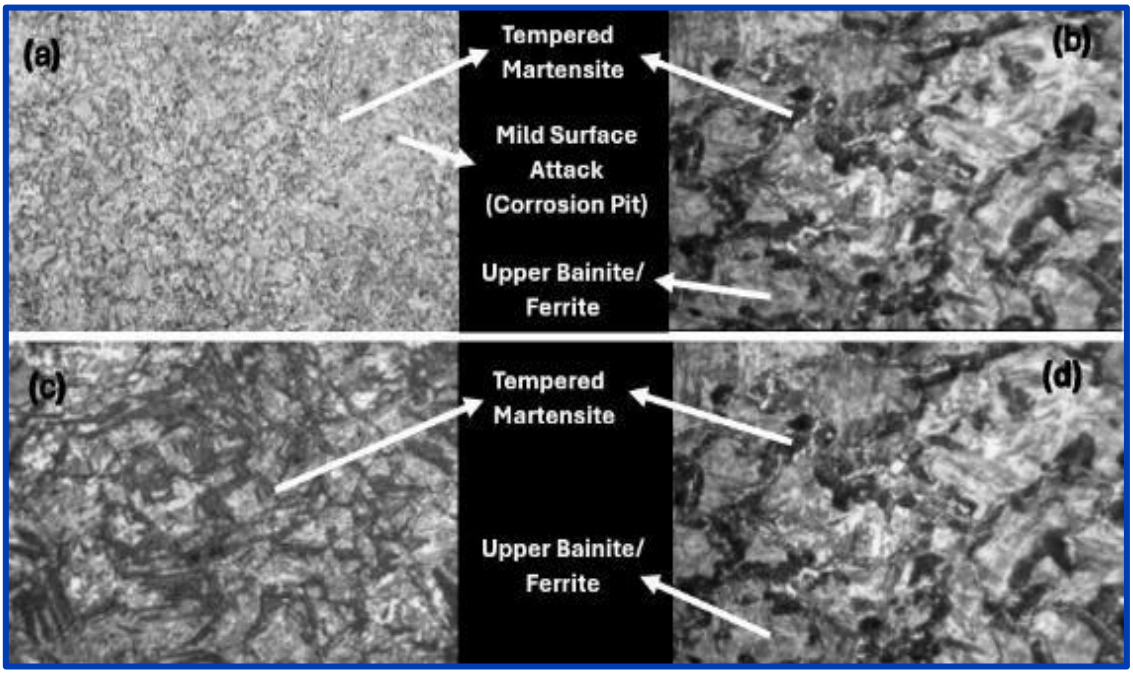


Figure 3: Optical micrographs of the AISI 1035 steel sample quenched in Gaberoun lake water and subsequently tempered at 600°C for 30 min soaking time

Figure 3(a): The microstructure is characterised by a fine, dark-etching matrix, which is typical of **tempered martensite**. The prior austenite grain boundaries are faintly visible, indicating the lath-like nature of the martensite structure. The tempering process has caused the precipitation of fine carbide particles within the martensite laths, which is not resolvable at this magnification but contribute to the overall dark appearance. Additionally, the dark spots are not part of the bulk microstructure but are a sign of a surface attack, possibly pitting corrosion after the quenching process, which is consistent with the remarkably high chloride content of Gaberoun lake water, which is 70 mg/l compared with other quenchants. However, surface attack (corrosion pitting) can be reduced by increasing soaking time.

Figure 3(b): The image shows a region with a slightly coarser structure, suggesting the presence of a small fraction of **upper bainite** or **ferrite** alongside the tempered martensite. The variation in etching contrast across the field of view is indicative of a mixed microstructure, which can occur when the quenching medium (lake water) has a lower cooling rate than pure or natural water

Figure 3(c): In this image a more uniform distribution of the fine, tempered martensite was observed. The structure is highly refined, which correlates with the high hardness average value (51 HRC) reported for this sample in Table 5, as a finer martensitic structure generally provides superior strength.

Figure 3(d): This micrograph highlights the overall homogeneity of the tempered structure. The absence of large, distinct white areas (untempered martensite or massive ferrite) confirms that the austenitizing and tempering treatments were effective in producing a relatively uniform, high-strength microstructure.

5.2 Microstructures analysis of seawater quenched samples

Figure 4 (a, b, c, d) displays the microstructure of the AISI 1035 carbon steel sample quenched in Mediterranean seawater and tempered at 600°C for 30 min soaking time. Seawater, due to its dissolved salts, typically acts as a more severe quenchant than natural water, leading to a higher proportion of martensite.

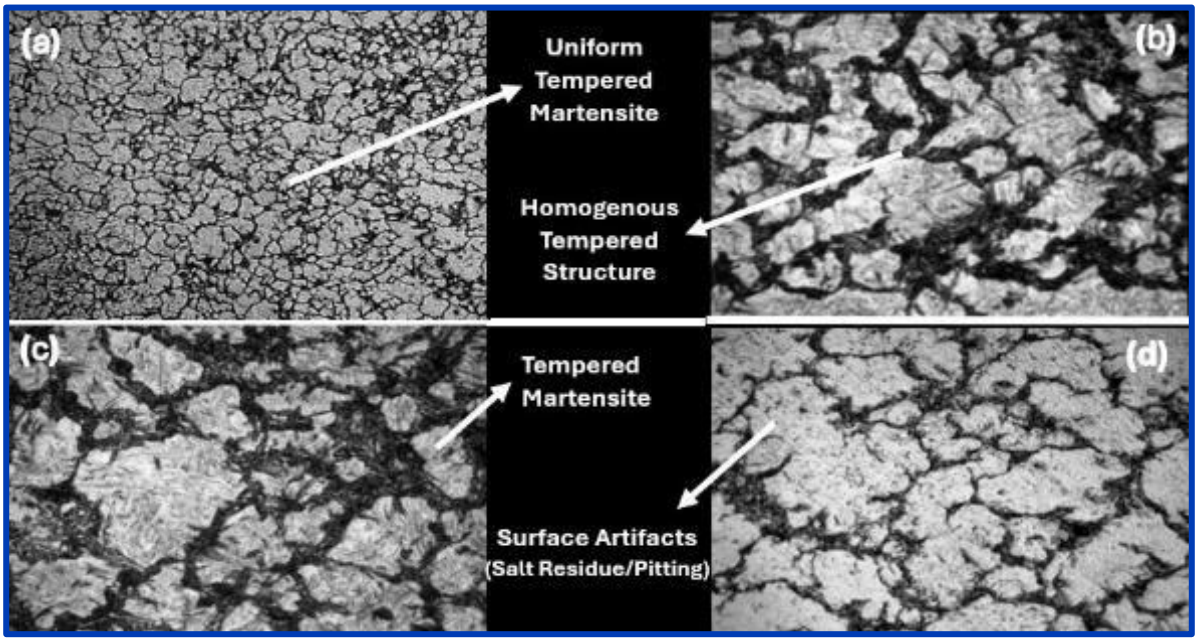


Figure 4: Optical micrographs of the AISI 1035 steel sample quenched in seawater and subsequently tempered at 600°C for 30 min soaking time

Figure 4(a) shows a predominantly **tempered martensite** structure, similar to the lake water sample, but with potentially finer laths due to the higher severity of the seawater quenchant. The matrix is dark and featureless at this magnification, confirming the successful transformation and subsequent tempering of the martensite.

Figure 4(b): This micrograph reveals evidence of surface interaction, likely due to the corrosive nature of the seawater. The dark lines and spots are not part of the bulk microstructure but are artefacts of surface degradation, possibly **pitting corrosion or salt residue** from the quenching process, which is consistent with the high chloride content of seawater.

Figure 4(c): This image confirms the presence of surface defects, such as micro-cracks or localised corrosion pits, is more pronounced here. These features are external to the metallic microstructure and are a direct consequence of the aggressive quenching environment. The underlying metallic structure remains the fine, dark-etching tempered martensite.

Figure 4(d): Similarly, this image further illustrates the effect of the seawater environment on the sample surface. The interconnected dark features suggest an advanced stage of surface attack, which could negatively impact the fatigue life and

overall surface integrity of the component. The bulk microstructure, however, is a fine tempered martensite, correlating with the high hardness achieved (43 HRC).

5.3 Microstructures analysis of natural water quenched samples

Figure 5 (a, b, c, d) shows the microstructure of the AISI 1035 carbon steel samples quenched in natural water and tempered at 600°C for 30 min soaking time. Natural water is generally the least severe quenchant compared to other tested quenchants, which may result in a higher fraction of softer transformation products.

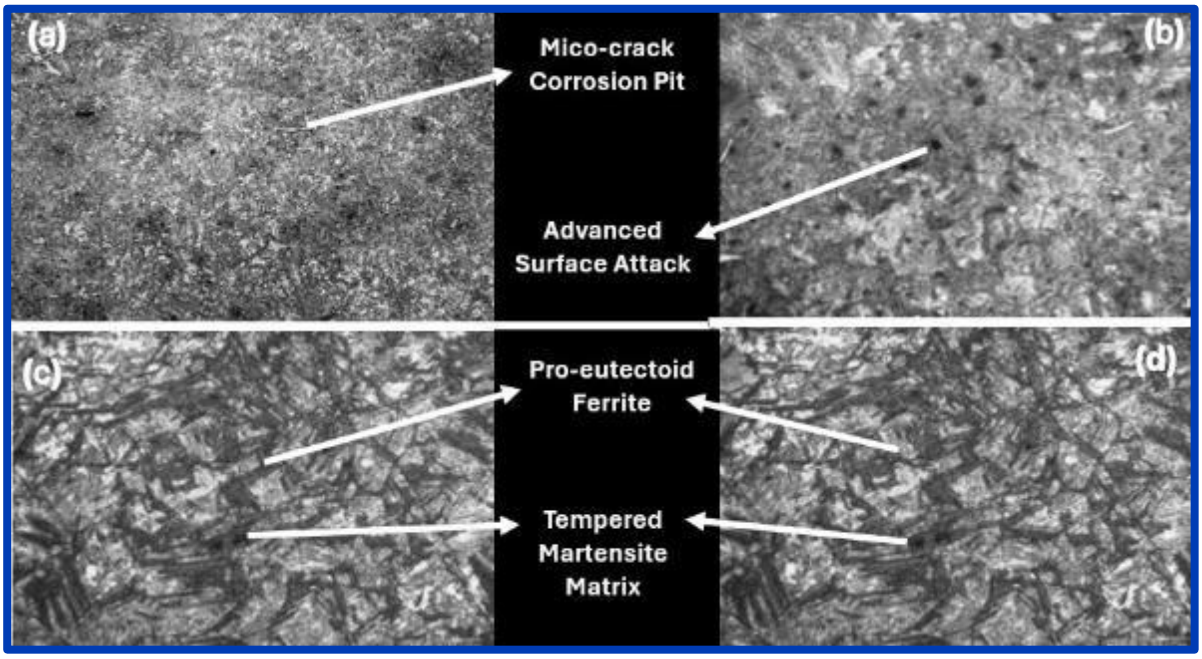


Figure 5: Optical micrographs of the AISI 1035 steel sample quenched in natural water and subsequently tempered at 600°C for 30 min soaking time

Figure 5(a): The microstructure is a mixture of **tempered martensite** (dark-etching areas) and a noticeable amount of **ferrite** (light-etching, blocky areas) and/or **pearlite** (lamellar structure, possibly invisible at this magnification level). The presence of these softer phases is a result of the lower cooling rate of the natural water, which allowed for partial transformation to non-martensitic products.

Figure 5(b): This image appears to show the prior **austenite grain structure** at a higher temperature or a region where the transformation was incomplete. However,

based on the context of the other images, it is more likely a region showing the mixed ferrite-martensite structure, with the ferrite outlining the grain boundaries.

Figure 5(c): This micrograph clearly shows the presence **of pro-eutectoid ferrite** (the light, blocky phase) distributed along the prior austenite grain boundaries. The remaining matrix is tempered martensite. This mixed structure explains the lowest hardness average value (28 HRC) reported for this sample, as shown below in Table 5, as the softer ferrite phase significantly reduces the overall hardness.

Figure 5(d): This image describes the growth of austenite grains. While the image may show grain boundaries, the final structure is a result of the quenching and tempering. The big differences in size and mixed crystals mentioned in the original text are likely a misinterpretation of the **mixed ferrite and tempered martensite** phases, where the blocky ferrite regions are mistaken for large grains. The overall structure is a heterogeneous mix of soft ferrite and hard tempered martensite.

6. Hardness analysis

Hardness test measurements were performed using HST Rockwell Vickers hardness tester, as shown in Figure 6. Hardness measurements of nine quenched samples were taken similarly at three positions, i.e. perpendicular to both edges and at the centre of each quenched sample. The hardness results are depicted in Figure 7.



Figure 6: Image of HST Rockwell Vickers hardness tester used in the research

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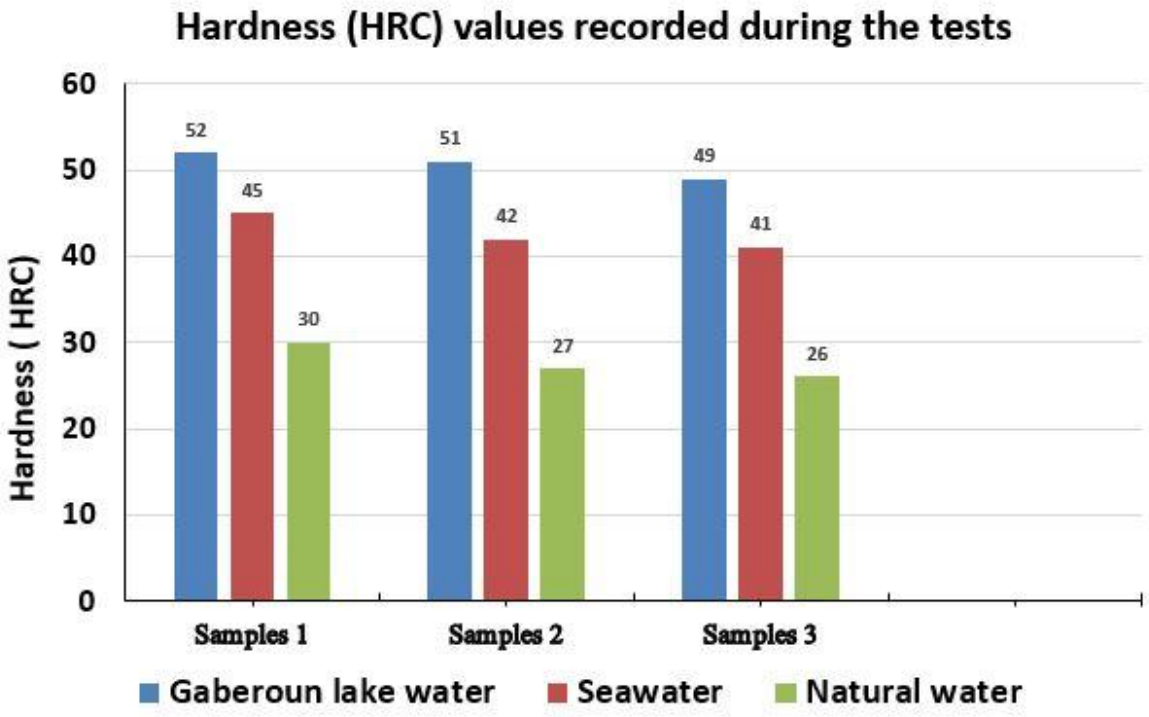


Figure 7: Hardness (HRC) values recorded during the experimentation

Figure 7, clearly shown that samples quenched by Gaberoun lake water exhibited the highest hardness values (52, 51, 49 HRC) with an average of 51 HRC. This indicates that Gaberoun lake water produced the most severe cooling rate among the three quenching media. The high hardness correlates directly with the formation of a predominantly martensitic microstructure, characterised by fine lath martensite and possibly a small amount of retained austenite. The mineral-rich composition and relatively high salinity of the lake water enhanced the heat extraction rate, promoting rapid austenite-to-martensite transformation with minimal diffusion-controlled products like bainite or pearlite. The slight drop in hardness from sample 1 to 3 suggests minor variations in bath temperature or vapour film behaviour, but all remain within the martensitic domain. After tempering at 600°C, the martensite partially decomposed into tempered martensite with finely dispersed carbides, yet the base hardness remained high due to the prior fast quench. Samples quenched by Mediterranean seawater exhibited moderate hardness values (45, 42, 41 HRC) with an average of 43 HRC. This suggests a medium cooling severity, resulting in a mixed microstructure composed of martensite and upper bainite. Seawater's high chloride and salt content alters the boiling behaviour, forming a more stable vapour film at

early stages, which can reduce the instantaneous heat transfer rate compared with Gaberoun lake water. Consequently, the cooling rate was sufficient to form martensite in the surface regions but allowed bainitic transformation at the core or grain boundaries. The microstructure after tempering likely consists of tempered martensite with dispersed carbides and bainitic ferrite, giving intermediate hardening. Samples quenched by natural water showed the lowest hardness values (30, 27, 26 HRC) with an average of 28 HRC. This demonstrates that fresh water provided the least cooling rate, leading to the development of bainitic and pearlitic microstructures with limited martensite formation. Because natural water has lower salinity and fewer dissolved ions, its boiling and vapour film stability reduces convective heat transfer, thus producing slower cooling and greater time for diffusion-controlled transformations. All in all, the resulting microstructure after the tempering process consists mainly of tempered bainite and ferrite-pearlite, characterised by softer phases and lower hardness. This condition promotes better ductility and toughness, but at the expense of hardness.

7. Impact Energy analysis

An impact energy test is a mechanical test used to measure a material's toughness by determining the amount of absorbed energy before fracture when subjected to a sudden load or impact. All nine quenched samples were prepared based on the standard Charpy test sample (10 mm x 10 mm x 60 mm in length) as shown below in Figure 8. The Impact energy results are presented in Figure 9.

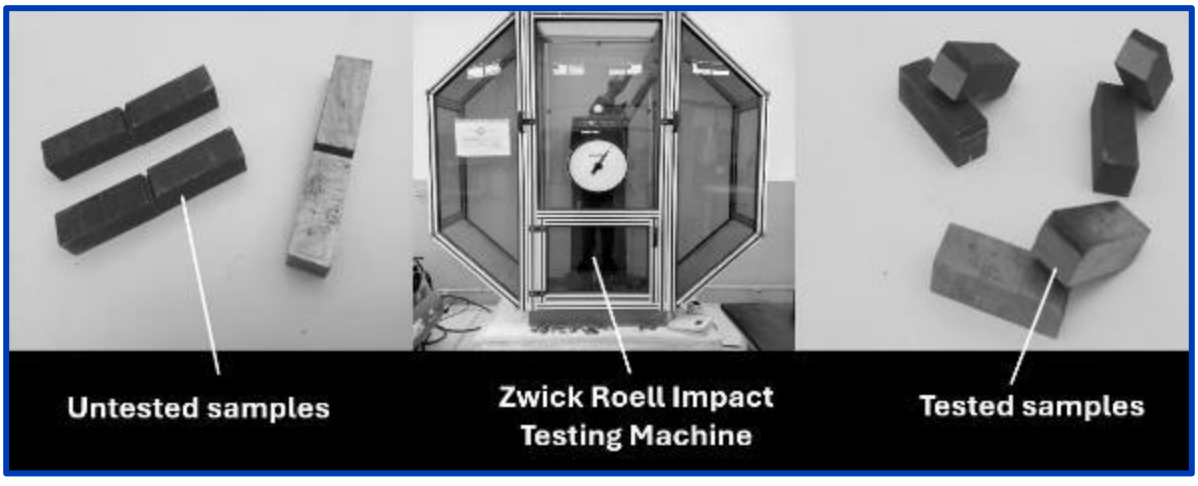


Figure 8: Image of prepared and examined specimens after impact energy test using Zwick/ Roell impact machine

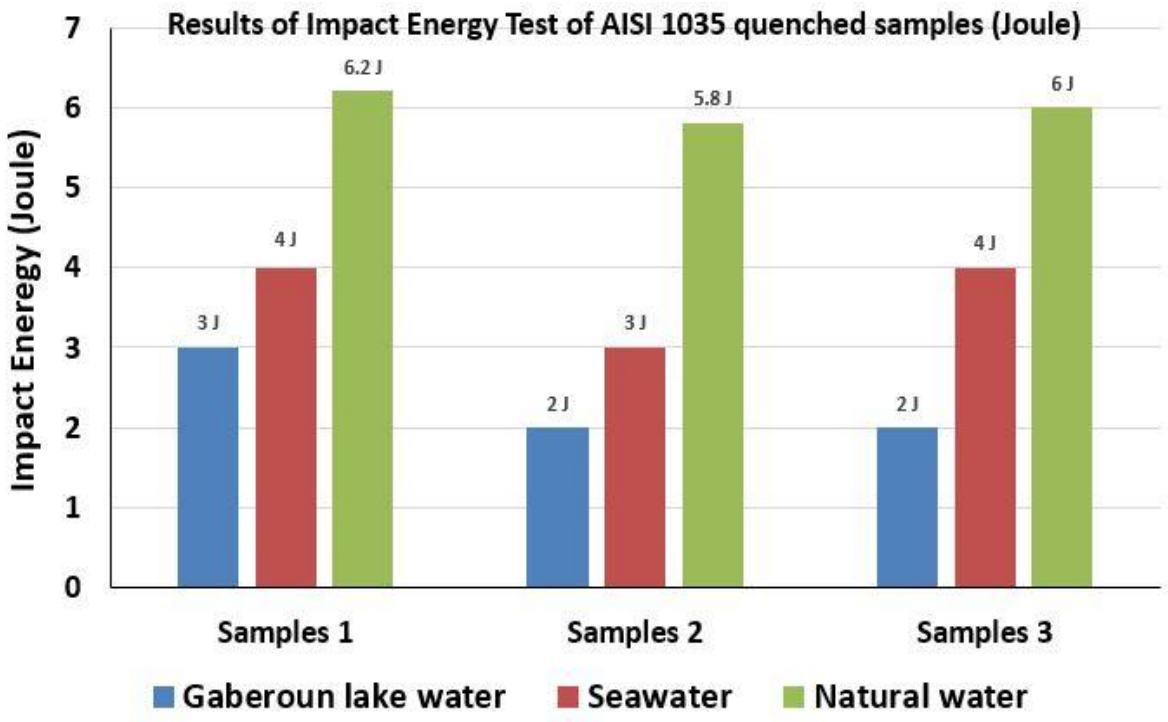


Figure 9: Results of impact energy test for AISI 1035 quenched samples (Joule)

The results shown above in Figure 9 confirm the inverse relationship between the hardness and impact absorbed energy: the more severe quenchant (Gaberoun lake water) produced higher hardness but lower toughness, while the milder quenchant (Mediterranean seawater) generated moderate hardness and toughness. Natural water quenchant achieved lower hardness but higher impact energy (better toughness). These findings are in agreement with results by [10,11] who found that the relationship between hardness and impact absorbing energy is inverse. Finally, it can be said that the tempering at 600°C for 30 min soaking time modified all martensitic matrices, but the initial martensite fraction determined how much softening and toughness improvement was possible.

8. Conclusion

The study effectively demonstrates that the chemical composition of the quenching water significantly influences the cooling rate, which in turn dictates the final

microstructure and, consequently, the mechanical properties of the heat-treated AISI 1035 carbon steel. The following conclusions can be drawn:

- Hardness is maximised by the highest quenching severity, which produces a high-volume fraction of tempered martensite (Gaberoun Lake Water, 51 HRC).
- Signs of mild corrosion pitting were observed on Gaberoun lake water quenched samples after the quenching process due to a notable presence of the chloride element in the quenchant.
- Impact Energy is maximised by the lowest quenching severity, which results in a mixed microstructure containing a significant amount of the ductile ferrite phase (Natural Water, 6 J).
- The inverse relationship between hardness and impact energy is confirmed, highlighting the necessity of selecting a heat treatment process that balances strength and toughness for the intended application.
- It was observed that the use of corrosive media like Mediterranean seawater introduces surface integrity issues (corrosion and cracking), which can negatively affect mechanical performance, particularly fatigue and impact resistance.

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