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Assessment of Silt as a Sustainable Raw Material in High Sulfate Resistant Oil-Well Cement

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ABSTRACT

This study investigates the feasibility of using natural silt as a partial substitute for clay in the production of high sulfate-resistant (HSR) oil-well cement. The research involved the chemical characterization of locally sourced raw materials — including silt, limestone, iron ore, and gypsum — followed by the design and preparation of raw mixes tailored to meet the requirements of API Specification 10A and the Iraqi Standard Specification No. 5 (2019).

Clinker was synthesized under controlled laboratory conditions, and comprehensive chemical and physical tests were carried out on the produced cement. Chemical evaluations included oxide composition and phase estimation (C_3S, C_3A, etc.), calculated via Bogue's equations, while physical testing covered slurry density, thickening time, free fluid content, compressive strength (at 8 and 24 hours), and detailed rheological behavior.

The results demonstrated that the incorporation of silt improved the silica-to-alumina ratio, minimized the reliance on expensive iron ore by reducing its content from 6% to 3%, and maintained C_3A and C_3S levels within standard limits. Cement samples incorporating silt exhibited excellent slurry properties, with density ranging from 1.87 to 1.89 g/cm³, thickening times within the API recommended window (90–120 min), and negligible free fluid. Compressive strength values exceeded 800 psi after 8 hours and reached over 1600 psi after 24 hours, confirming full compliance with API criteria.

Additionally, rheological testing revealed stable flow behavior and suitable yield points, confirming good pumpability and workability of the cement slurry. When compared to the control cement (produced without silt), the silt-modified samples showed comparable or slightly improved performance across most parameters, with only minor reductions in early compressive strength due to slightly lower C_3S content.

Overall, this research highlights the technical viability and economic benefits of partially replacing clay with locally available silt in HSR oil-well cement. The findings confirm that silt can serve as a sustainable raw material, reducing production costs and raw material consumption, while ensuring compliance with international cementing standards. These outcomes have strong implications for future large-scale applications in Iraqi cement plants and oilfield operations

Keyword: Oil-well cement; Silt substitution; Clay replacement; High sulfate resistance; API 10A; Clinker quality

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1- Introduction

Cement is a fundamental material in the construction and energy sectors, composed primarily of calcium–aluminosilicate compounds that hydrate to form strength-giving phases. Among its specialized types, oil-well cement plays a critical role in providing zonal isolation, casing support, and long-term well integrity under harsh downhole conditions involving high pressure, temperature, and chemical exposure.

To meet such demands, cement must conform to strict criteria outlined in API Specification 10A [1], including standards for slurry stability, thickening time, compressive strength, and sulfate resistance. In recent years, research has focused on enhancing these properties using alternative raw materials and additives such as nanosilica, calcined clays, and industrial byproducts, which have shown promising improvements in mechanical strength and durability under high-pressure high-temperature (HPHT) conditions [2–4].

In Iraq, the growing demand for oil-well cement—driven by ongoing petroleum exploration—has underscored the importance of utilizing locally available and sustainable materials. Traditional clay, while commonly used as a siliceous-aluminous source, often contains elevated alumina levels that may promote the formation of undesirable secondary phases. In contrast, natural silt deposits, abundant in northern Iraq, are richer in silica and contain relatively lower alumina. Their use may reduce dependence on costly or limited materials like iron ore, improve silica-to-alumina balance, and reduce fuel consumption during clinker production [5–7].

Despite the growing global interest in sustainable cement formulations, few studies have directly explored the use of silt as a partial substitute for clay in high sulfate-resistant (HSR) oil-well cement. This study addresses that gap by evaluating the chemical and physical performance of cement produced with silt, and by assessing its compliance with API and Iraqi specifications [8,9].

Given Iraq's position as one of the world's major oil producers, there is a critical need for locally tailored solutions that enhance oil-well cement performance while reducing production costs. Conventional clay sources often contain high alumina, which can promote the formation of undesirable hydration phases and reduce long-term durability. By contrast, natural silt deposits, particularly those found in northern Iraq, offer a more favorable silica-to-alumina ratio, are more abundant, and are generally less expensive. Utilizing silt can also reduce the demand for costly iron ore, which is often imported or sourced from distant quarries, thereby lowering both material and fuel consumption during clinker production [10–13].

This study seeks to demonstrate that silt incorporation not only satisfies chemical and physical standards for oil-well applications at varying depths but also contributes to sustainable industrial practices within the Iraqi cement industry. The outcomes of this research are expected to support a shift toward resource-efficient manufacturing and increased reliance on locally available geological materials. Similar directions have been emphasized in recent studies focusing on ecological additives and pozzolanic replacements in well cementing [14–17].

2- Materials and methods

2.1 Raw Materials

The raw materials used in this study were locally sourced from northern and western Iraq. Limestone was obtained from the Fatha Formation quarries and served as the main source of calcium carbonate ($CaCO_3$). Clay samples were collected from recent valley deposits near the same quarries and were characterized by elevated silica (SiO_2) and alumina (Al_2O_3) contents. Iron ore was obtained from the Hussainiyat Formation in the Western Desert and is rich in ferric oxide (Fe_2O_3). Silt was collected from recent fluvial deposits along the Tigris River in Nineveh Governorate; it is predominantly siliceous with moderate alumina and

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represents the primary substitution material in this study. Gypsum, sourced from the Fatha Formation, was added during final grinding to regulate cement setting time.

2.2 Preparation of Raw Mix and Clinker

Two primary raw mix designs were prepared in this study to evaluate the effect of silt incorporation on the production of high sulfate-resistant (HSR) oil-well cement. The first mix, formulated without silt, consisted of 65% limestone, 30% clay, and 5% iron ore. In contrast, the second mix included silt as a partial replacement for clay and was composed of 71% limestone, 20% silt, 6% clay, and 3% iron ore. All raw materials were first dried, crushed, and homogenized before analysis. Their oxide compositions were determined using X-ray fluorescence (XRF; PANalytical Axios, Netherlands). Based on the XRF results, the raw mixes were adjusted to achieve the standard oxide ratios required for high sulfate-resistant (HSR) oil-well cement, in accordance with API Specification 10A [1] and the Iraqi Standard Specification No. 5 [2]. The mixes were then burned in a laboratory kiln under controlled temperatures to produce clinker. Afterward, the clinker was ground together with gypsum in a laboratory mill to obtain the final cement product.

It is important to note that only two main mixes were produced in this study, one with and one without silt, because the chemical compositions and performance characteristics of both Class B and Class G cement types were found to be highly comparable before and after silt addition. As a result, further mix variations were deemed unnecessary, and the analysis focused on these two representative formulations.

2.3 Chemical Analysis

The produced cement was analyzed to determine the main oxide contents (CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, SO_3, loss on ignition [L.O.I], and insoluble residue [IR]). Phase compositions (C_3S, C_2S, C_3A, and C_4AF) were calculated from Bogue equations to evaluate clinker quality and compliance with HSR specifications (1,18).

2.4 Physical Testing

Physical properties of the cement were determined in accordance with API Specification 10A [1] and Iraqi Standard No. 3210 (1987) [9] using standard laboratory equipment.

- **Fineness (Blaine specific surface)** was measured using the Blaine air permeability [19].
- **Soundness** was determined with an autoclave expansion test to evaluate volumetric stability.
- **Slurry density** was measured using a standard mud balance (g/cm^3).
- **Thickening time** was determined with a Consistometer (Chandler Model 90, USA) under simulated downhole pressure and temperature.
- **Free fluid content** was measured according to API procedures by quantifying water separation from a 250 ml slurry cylinder.
- **Compressive strength** was tested on 25 mm cement cubes cured under simulated well conditions (38 °C and 60 °C) for 8–24 h, then loaded to failure using a hydraulic press.
- **Rheological properties** (600–6 rpm readings, plastic viscosity, yield point, and gel strength) were measured according to **API RP 10B-2** to assess pumpability and slurry stability.

3- Results and Discussion

The chemical composition of the raw materials, as presented in Table 1, confirms their suitability for producing high-sulfate-resistant oil-well cement. According to the Iraqi Standard Specification No. 5 (2019) [8] and the API Specification 10A (2010) [1], achieving a proper balance among the main oxides — CaO, SiO_2, Al_2O_3, and Fe_2O_3 — is essential for producing a clinker with stable mineral phases and reliable performance under downhole conditions.

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The **limestone** samples exhibited high CaO content (51.83%)**,** which is essential as the primary calcium source in the clinker. The clay samples showed elevated levels of SiO_2 (36.02%) and Al_2O_3 **(**8.43%), values that are typical for argillaceous raw materials. However, excessive alumina can promote the formation of unwanted secondary phases, such as calcium aluminates, which negatively impact the long-term durability of the cement.

In contrast, **silt** was found to be significantly richer in SiO_2 (47.0%) and contained moderate Al_2O_3 (10.7%), offering a more balanced composition. This indicates that partial replacement of clay with silt can reduce the overall alumina content of the raw mix while increasing silica availability, thus favoring the formation of stable silicate phases in the clinker.

Iron ore, which recorded a very high Fe_2O_3 content (47.78%), remains the primary contributor of ferric oxide in the mix. However, due to its high cost and limited availability in Iraq, its usage in large proportions is economically restrictive. Alternatively, silt, with a Fe_2O_3 content of 9.3%, offers a viable option for reducing the required iron ore addition while still maintaining the necessary chemical balance. This approach aligns with recent findings advocating the use of alternative siliceous and argillaceous materials to reduce reliance on costly raw inputs without compromising cement quality [5,11].

Finally, gypsum, used during final grinding, exhibited a dominant SO_3 content of 37.77%, which meets the requirements for controlling the thickening time of cement slurry in accordance with API 10A [1], ensuring effective wellbore sealing.

Overall, the chemical composition results confirm that the inclusion of silt as a substitute for part of the clay is both technically and economically advantageous. It improves the silica-to-alumina ratio of the raw mix, reduces dependence on iron ore, and aligns with the chemical requirements of API 10A [1] and the Iraqi Standard [8]. These findings are in agreement with previous studies that highlighted the potential of locally available materials to enhance cement quality while lowering production costs [3,7].

Table 1. Percentage of oxides of the raw materials used for oil-well cement production

Oxides	Limestone	Clay	Iron Ore	Silt	Gypsum
SiO_2	2.59	36.02	16.12	47.0	10.17
Al_2O_3	0.63	8.43	3.2	10.7	2.39
Fe_2O_3	0.52	4.32	47.78	9.3	1.23
CaO	51.83	22.2	12.01	13.1	36.46
MgO	0.2	5.0	2.91	4.3	0.99
SO_3	0.1	0.9	2.3	0.1	37.77
L.O.I	42.83	22.08	14.59	13.6	10.67
Total	98.7	98.95	98.91	98.1	99.68

Chemical Properties and Specifications of Oil-Well Cement

The chemical properties and quality of both the clinker and the produced oil-well cement depend primarily on the selection of raw materials and the degree of their homogenization before burning in the kiln. Maintaining a proper chemical balance is essential to ensure the formation of stable mineral phases and adequate cement performance under downhole conditions.

Table 2 presents the required chemical specifications for different classes of oil-well cement within the Ordinary Grade (Class O), as defined by the American Petroleum Institute Specification 10A (2010) [1]. These limits mainly apply to Classes A, B, and C, while for Classes D through H, chemical parameters are generally not specified or are governed by performance-based criteria.

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Table 2. Chemical specifications of oil-well cement (Ordinary Grade – Class O) according to API Specification 10A[1]

Oxides and Parameters	Class A	Class B	Class C	Classes D, E, F	Class G	Class H
Magnesium Oxide (MgO), Max %	6.0	NA	6.0	NA	NA	NA
Sulfur Trioxide (SO_3), Max %	3.5	NA	4.5	NA	NA	NA
Loss on Ignition (L.O.I), Max %	3.0	NA	3.0	NA	NA	NA
Insoluble Residue (IR), Max %	0.75	NA	0.75	NA	NA	NA
Tricalcium Aluminate (C_3A), Max %	NR	NA	15.0	NA	NA	NA

Notes: NA = Not Applicable ,NR = No Requirement

.It is important to note that for Classes D to H, API Specification 10A [1] focuses more on physical performance parameters rather than chemical composition, especially when the cement is intended for use in more severe wellbore environments.

Moderate Sulfate Resistant Grade (MSR)

Oxides and Parameters	**A**	**B**	**C**	**D,E,F**	**G**	**H**
Magnesium Oxide, MgO (Max %)	NA	6.0	6.0	6.0	6.0	6.0
Sulfur Trioxide, SO_3 (Max %)	NA	3.0	3.5	3.0	3.0	3.0
Loss on Ignition, L.O.I (Max %)	NA	3.0	3.0	3.0	3.0	3.0
Insoluble Residue (Max %)	NA	0.75	0.75	0.75	0.75	0.75
Tricalcium Silicate, C_3S (Max %)	NA	NR	NR	NR	58	58
Tricalcium Silicate, C_3S (Min %)	NA	NR	NR	NR	48	48
Tricalcium Aluminate, C_3A (Max %)	NA	8	8	8	8	8
Alkalis as Na_2O Equivalent (Max %)	NA	NR	NR	NR	0.75	0.75

NA = Not Applicable, NR = No Requirement

Following the review of chemical specifications for Ordinary and Moderate Sulfate Resistant (MSR) cement grades, laboratory testing was conducted on Iraqi oil-well cement to verify its compliance with API Specification 10A [1]. The tests focused on Classes B and G, which are commonly used in oilfield operations across Iraq.

Chemical analyses were carried out at the Al-Hadbaa Cement Plant laboratory, while physical performance tests were conducted at the North Oil Company laboratories, using samples of high sulfate-resistant (HSR) oil-well cement. The tested samples included both Class B and Class G, as summarized in Table 3

Table 3. Physical specifications of oil-well cement classes according to API Specification 10A[1]

Physical Tests	A	B	C	D	E	F	G	H
Water-to-cement ratio (% by weight)	46	46	56	38	38	38	44	38
Fineness (Specific Surface, Min) (m^2/kg)	150	160	220	NR	NR	NR	NR	NR
Free Fluid Content (Max, mL)	NR	NR	NR	NR	NR	NR	3.5	3.5

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Compressive Strength at 8 Hours

Temp (°C)	Pressure (Psi)	Minimum Strength (Psi)
38 (Atmos.)	250	A: 200, B: 300, G: 300, H: 300
60 (Atmos.)	NR	G: 1500, H: 1500
110	3000	D: 500
143	3000	E: 500
160	3000	F: 500

Compressive Strength at 24 Hours

Temp (°C)	Pressure (Psi)	Minimum Strength (Psi)
38 (Atmos.)	1800	A: 1500, B: 2000
77	3000	D: 1000, E: 1000
110	3000	D: 2000, F: 1000
143	3000	E: 2000
160	3000	F: 1000

Thickening Time (API Spec. 10)

API Spec. No.	Max. Viscosity (B2)	Thickening Time (Min.–Max.)
4	30	90 min
5	30	G, H: 90–120 min
6	30	D, E, F: ≥100 min
8	30	E: 154 min
9	30	F: 190 min

Table 4 summarizes the chemical composition of high sulfate-resistant (HSR) oil-well cement produced at Al-Hadbaa Cement Plant for Classes B and G, formulated from limestone and clay with the addition of 6% iron ore and without any silt substitution. The results indicate that the main oxide components fall within the permissible ranges of API Specification 10A [1] for HSR cement.

For Class G, the cement contained 63.09% CaO, 2.20% SiO_2, 4.46% Al_2O_3, and 5.93% Fe_2O_3, with minor components including 2.27% MgO, 2.40% SO_3, and 1.51% LOI. The phase composition included C_3S = 52.29% and C_3A = 1.79%, both fully compliant with API requirements ($C_3A \leq 3\%$; C_3S range 48–65%). The insoluble residue (0.40%) and Na_2O equivalent (0.50%) were also well below the maximum allowable limits.

Similarly, Class B cement showed a comparable composition, with 62.56% CaO, 20.19% SiO_2, **4**.66% Al_2O_3, 5.93% Fe_2O_3, 2.20% MgO, and 2.04% SO_3. The phase calculations gave **C_3S =** 50.90% and C_3A = 2.32%, remaining below the specified thresholds. Insoluble residue was 0.60%, while the Na_2O equivalent was **0.40%**, both within the required limits.

Overall, the results demonstrate that both Class B and Class G cements produced without silt substitution exhibit a balanced chemical composition, stable clinker phases, and compliance with the API 10A [1] requirements for HSR oil-well cement, thus providing a reliable reference baseline for comparison with the silt-modified formulations.

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Table 4. Chemical test results of high sulfate-resistant (HSR) oil-well cement from Al-Hadbaa Cement Plant, Classes B and G, compared with API Specification 10A [1] requirements.

Chemical Requirements	Class G (HSR) – Test Results	Class G (HSR) – API Limits	Class B (HSR) – Test Results	Class B (HSR) – API Limits
SiO_2 (%)	2.20	NR	20.19	NR
Al_2O_3 (%)	4.46	NR	4.66	NR
Fe_2O_3 (%)	5.93	NR	5.93	NR
CaO (%)	63.09	NR	62.56	NR
MgO (%)	2.27	6.0 (Max)	2.20	6.0 (Max)
SO_3 (%)	2.40	3.0 (Max)	2.04	3.0 (Max)
L.O.I (%)	1.51	3.0 (Max)	1.36	3.0 (Max)
Total	99.86	NR	98.94	NR
Insoluble Residue (%)	0.40	0.75 (Max)	0.60	0.75 (Max)
C_3S (%)	52.29	48–65	50.90	NR
C_3A (%)	1.79	3.0 (Max)	2.32	3.0 (Max)
$C_4AF + 2C_3A$ (%)	21.62	24 (Max)	22.68	24 (Max)
Na_2O Equivalent (%)	0.50	0.75 (Max)	0.40	NR

NR = No Requirement, Max = Maximum Allowable Limit

Table 5 presents the physical properties of high sulfate-resistant (HSR) oil-well cement, Classes B and G, produced at Al-Hadbaa Cement Plant from limestone and clay with the addition of 6% iron ore and without any silt substitution. The results confirm that both classes meet the requirements of API Specification 10A [1], with suitable slurry density, acceptable thickening times, low free fluid content, adequate compressive strength development, and stable rheological behavior. These findings establish a solid baseline for evaluating the performance of silt-modified cement formulations.

Table 5. Physical test results of high sulfate-resistant (HSR) oil-well cement, Classes (B) and (G), from Al-Hadbaa Cement Plant, compared with API Specification 10A[1]

Cement Class (B)

No.	Property	Standard Requirements	Test Results
1	Slurry Density (g/cc)	—	1.86
2	Thickening Time at 113 °F, 3870 psi (min)	90 min	113.5
3	Free Fluid Content (ml)	—	0.90
4	Compressive Strength, 8 h at 38 °C (psi)	200 min	823
5	Compressive Strength, 24 h at 38 °C (psi)	1500 min	1675
6	Dry Cement Density (g/cc)	—	3.16

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Rheology Parameters (Class B):

Parameter	Test Results
Ø 600	77
Ø 300	61.5
Ø 200	55
Ø 100	45.5
Ø 60	42
Ø 30	38
Ø 6	24
Gel 0	17.5
Gel 10	18
M.P	15.5
Y.P	46

Cement Class (G)

No.	Property	Standard Requirements	Test Results
1	Slurry Density (g/cc)	—	1.89
2	Thickening Time at 125 °F, 5170 psi (min)	90–120	106
3	Free Fluid Content (ml)	Max 3.5	0.75
4	Compressive Strength, 8 h at 38 °C (psi)	Min 300	749
5	Compressive Strength, 8 h at 60 °C (psi)	Min 1500	1899
6	Dry Cement Density (g/cc)	—	3.15

Rheology Parameters (Class G):

Parameter	Test Results
Ø 600	93.2
Ø 300	71.8
Ø 200	63.3
Ø 100	52.3
Ø 60	47.3
Ø 30	42
Ø 6	22.8
Gel 0	18
Gel 10	23
M.P	21.5
Y.P	50.3

The physical properties presented in Table 5 confirm that both Class B and Class G cements produced without silt substitution fully comply with the requirements of API Specification 10A [1]. Slurry densities were stable at 1.86 g/cc for Class B and 1.89 g/cc for Class G, values consistent with operational standards. Thickening times were measured at 113.5 minutes for Class B (113 °F, 3870 psi) and 106 minutes for Class G (125 °F, 5170 psi), both falling within the API recommended range of 90–120 minutes. Free fluid contents were negligible (0.90 ml for Class B and 0.75 ml for Class G), well below the maximum allowable

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3.5 ml, indicating excellent slurry stability. Compressive strength development was satisfactory, with Class B achieving 823 psi after 8 hours and 1675 psi after 24 hours at 38 °C, while Class G recorded 749 psi at 8 hours (38 °C) and 1899 psi at 8 hours (60 °C). Dry cement densities were consistent (3.16–3.15 g/cc). Rheological measurements for both classes confirmed stable flow curves and yield points, reflecting good pumpability and operational performance.

These results demonstrate that the reference formulations of Class B and Class G provide reliable physical properties in line with international standards, thereby serving as a robust baseline for evaluating the performance of silt-modified cement.

Table 6 presents the chemical composition of high sulfate-resistant (HSR) oil-well cement produced at Al-Hadbaa Cement Plant for Classes B and G with the incorporation of silt, together with limestone and a reduced proportion of clay. In these mixes, the iron ore content was reduced to 3%, while maintaining the balance of the major oxides within the limits of API Specification 10A [1]. The results demonstrate that both Classes B and G meet the chemical requirements for HSR cement, confirming the technical feasibility of partially substituting clay with silt.

Table 6. Chemical test results of high sulfate-resistant (HSR) oil-well cement, Classes B and G, with the addition of silt instead of clay, from Al-Hadbaa Cement Plant, compared with API Specification 10A [1].

Chemical Requirements	Class G (HSR) – Test Results	Class G (HSR) – API Limits	Class B (HSR) – Test Results	Class B (HSR) – API Limits
SiO_2 (%)	20.63	NR	20.65	NR
Al_2O_3 (%)	4.70	NR	4.65	NR
Fe_2O_3 (%)	5.93	NR	5.87	NR
CaO (%)	63.62	NR	62.74	NR
MgO (%)	2.10	6.0 (Max)	2.30	6.0 (Max)
SO_3 (%)	1.71	3.0 (Max)	1.88	3.0 (Max)
L.O.I (%)	0.55	3.0 (Max)	1.18	3.0 (Max)
Total (%)	99.24	NR	99.27	NR
Insoluble Residue (%)	0.50	0.75 (Max)	0.55	0.75 (Max)
C_3S (%)	53.38	48–65	49.56	NR
C_3A (%)	2.47	3.0 (Max)	2.73	3.0 (Max)
$C_4AF + 2C_3A$ (%)	22.98	24 (Max)	22.66	24 (Max)
Na_2O Equivalent (%)	0.50	0.75 (Max)	0.25	NR

NR = No Requirement, Max = Maximum Allowable Limit

The chemical results in Table 6 confirm that both Class B and Class G cements incorporating silt comply with the requirements of API 10A and ISO 10426-1. Class G displayed superior compositional balance, with MgO (2.10%), SO_3 (1.71%), and insoluble residue (0.50%), all well below the maximum allowable limits. Class B exhibited slightly higher values of MgO (2.30%) and SO_3 (1.88%), yet still within the required thresholds. Both classes-maintained C_3A values below 3% (2.47% for Class G and 2.73% for Class B), ensuring adequate sulfate resistance.

The proportion of C_3S decreased slightly in Class B (49.56%) compared with Class G (53.38%), which may influence early strength development, while long-term performance remains unaffected. The Na_2O equivalent values (0.50% and 0.25%) also confirm safe margins against alkali–silica reactivity.

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Overall, the substitution of silt for clay resulted in well-balanced phase compositions, controlled minor oxides, and chemical purity that support the use of silt as a sustainable raw material for producing HSR oil-well cement.

Table 7 presents the physical test results of high sulfate-resistant (HSR) oil-well cement, Classes B and G, produced at Al-Hadbaa Cement Plant with the incorporation of silt and 3% iron ore. The tests were conducted to verify compliance with API Specification 10A [1] and the Iraqi Standard No. 5 (2019) [8]. The results confirm that both classes meet the physical performance requirements, with stable slurry density, acceptable thickening times, negligible free fluid content, adequate compressive strength development, and consistent rheological behavior.

Table 7. Physical test results of high sulfate-resistant (HSR) oil-well cement, Classes (B) and (G), produced with the addition of silt and 3% iron ore to the raw mix at Al-Hadbaa Cement Plant, compared with API Specification 10A

Cement Class (B)

No.	Property	Standard Requirements	Test Results
1	Slurry Density (g/cc)	—	1.87
2	Thickening Time at 113 °F, 3870 psi (min)	90 min	94.5
3	Free Fluid Content (ml)	—	Nil
4	Compressive Strength, 8 h at 38 °C (psi)	200 min	719.5
5	Compressive Strength, 24 h at 38 °C (psi)	1500 min	1640
6	Dry Cement Density (g/cc)	—	3.20

Rheology Parameters (Class B):

Parameter	Test Results
Ø 600	91.5
Ø 300	75.5
Ø 200	69.5
Ø 100	62.0
Ø 60	59.0
Ø 30	55.5
Ø 6	33.0
Gel 0	24.0
Gel 10	30.5
M.P	16.0
Y.P	59.5

Cement Class (G)

No.	Property	Standard Requirements	Test Results
1	Slurry Density (g/cc)	—	1.89
2	Thickening Time at 125 °F, 5170 psi (min)	90–120	97.5
3	Free Fluid Content (ml)	Max 3.5	1.3
4	Compressive Strength, 8 h at 38 °C (psi)	Min 300	810
5	Compressive Strength, 8 h at 60 °C (psi)	Min 1500	1590

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6	Dry Cement Density (g/cc)	—	3.18

The physical evaluation in Table 7 confirms that both Class B and Class G cements produced with silt incorporation fully comply with API 10A (2010) [1] and the Iraqi Standard No. 5 (1984) [20]. Slurry densities remained stable at 1.87–1.89 g/cc, while thickening times were 94.5 minutes for Class B and 97.5 minutes for Class G, both within the recommended API range (90–120 minutes). Free fluid contents were negligible (0 ml for Class B and 1.3 ml for Class G), significantly below the maximum allowable 3.5 ml, reflecting excellent slurry stability [2,25].

Compressive strength development was also satisfactory: Class B achieved 719.5 psi after 8 hours and 1640 psi after 24 hours (38 °C), while Class G reached 810 psi at 8 hours (38 °C) and 1590 psi at 8 hours (60 °C). Although a slight reduction in early strength was noted in Class G due to the decrease in C_3S content after silt substitution, long-term strength values remained well above the minimum API requirements. Similar observations have been reported, where silica-rich additives delay early hydration but enhance long-term stability [11,6,15,21].

Dry cement densities (3.18–3.20 g/cc) confirmed material consistency. Rheological results (Class B) demonstrated stable viscosity profiles, yield points, and gel strengths, indicating good flowability and pumpability. These findings are consistent with recent studies emphasizing that alternative siliceous materials can maintain reliable rheological stability in cement systems [16,22,23].

Collectively, these results clearly demonstrate that substituting silt for clay, while reducing iron ore content from 6% to 3%, does not adversely affect slurry density, stability, or rheology, and only marginally influences early strength. The produced cements maintain full compliance with international standards, validating the effectiveness of silt incorporation for oil-well cementing applications in Iraq [5,24].

4- Conclusion

- The chemical analyses confirmed that the incorporation of silt as a partial replacement for clay improved the **silica-to-alumina ratio** in the raw mix, reduced the required addition of iron ore, and ensured full compliance with **API Specification 10A** and the **Iraqi Standard No. 5 (2019).**
- The physical test results demonstrated that cements produced with silt exhibited slurry densities, thickening times, and rheological properties comparable to those of cements produced without silt, indicating that the substitution did not adversely affect **pumpability or workability.**
- A slight increase in **C_3A content** and a minor decrease in **C_3S content** were observed after silt incorporation; however, both parameters remained within API limits. Consequently, the cement maintained **adequate sulfate resistance** and acceptable strength development.
- **Compressive strength values** for both Class B and Class G cements consistently exceeded the minimum requirements of API 10A, confirming that silt-modified cement is suitable for oil-well cementing operations at various depths and conditions.
- From an economic perspective, the use of silt reduced dependence on costly and scarce iron ore, lowered fuel consumption during clinker production, and contributed to the manufacture of high-quality cement, thereby improving the feasibility of large-scale industrial application in Iraqi cement plants.
- Overall, the study demonstrates that silt can be successfully utilized as an alternative raw material in the production of HSR oil-well cement, ensuring compliance with international standards while supporting sustainable and cost-effective practices in the Iraqi cement industry.

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