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The Effect of Partial Replacement of GGBS on the Rheological Properties of Oil Well Cement Slurries

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Abstract

The rheological properties of cement slurries play a crucial role in the identification and mitigation of gas-migration issues in oil field applications. Rheological properties give for more fundamental investigation, more precise phenomenological description of flow properties and serve as datum for numerical simulations. Standard commercially available rheometers are typically utilized to implement those measurements. This work presents the constitutive modelling of cement slurries use cement type G as defined by the API. The categorisation established by the American Petroleum Institute is conducted at varying rates. Ground-grained blast furnace slag (GGBS) at 15% intervals ranging from 15% to 75%. Continued. Cement slurries often display multifaceted non-linear fluid behaviour, including viscoelasticity, yield stress, shear-thinning effects, thixotropy, and other related phenomena. Two crucial rheological properties of cement, the shear viscosity and the yield stress, have been intensively investigated. We found the optimal percentage of partial replacement of cement type G with GGBS, water/cement ratio, mixing methods, temperature, shear rate, pressure, and the thixotropic behavior of cement with GGBS. The result shows that when increase the partial replacement of GGBS the plastic viscosity and yield point increase with increase the percentage of GGBS and the optimal percentage is 45% and then decrease until reaching the percentage 75%.

Keywords: cement slurries; non-Newtonian fluids; rheology; viscosity; yield stress; GGBS and OWC.

تأثير الاستبدال الجزئي لخبث افران الصهر الحبيبية على الخصائص الريولوجية لملاط الاسمنت المستخدم في ابار النفط

الخلاصة:

تلعب الخصائص الريولوجية لملاط الاسمنت دورًا حاسمًا في تحديد وتخفيف مشاكل هجرة الغاز في تطبيقات حقول النفط. توفر خصائص الريولوجيا أساسًا لبحوث أكثر جوهرية، ووصف أكثر دقة لخصائص التدفق، وتعمل كبيانات مرجعية للمحاكاة العددية. عادةً ما يتم استخدام مقاييس اللزوجة القياسية المتوفرة تجاريًا لتنفيذ هذه القياسات. يعرض هذا العمل نمذجة لمحاليل الاسمنت باستخدام أسمنت من نوع G كما هو

محدد بواسطة معهد البترول الأمريكي (API). يتم إجراء الفحص بواسطة التصنيف الذي وضعه معهد البترول الأمريكي بمعدلات متغيرة يتم استخدام خبث افران الصهر الحبيبية GGBS بنسب تتراوح من 15% إلى 75%. غالبًا ما يظهر ملاط الأسمنت سلوكًا غير خطي، اللزوجة المرنة، وإجهاد الخضوع، التخفيف القصي، والانسيابية، وغيرها من الظواهر ذات الصلة. تم التحقيق بشكل مكثف في خاصيتين ريولوجيتين حاسمتين للأسمنت، وهما الزوجة البلاستيكية وإجهاد الخضوع. وجدنا النسبة المثلى للاستبدال الجزئي لنوع الأسمنت G بخبث افران الصهر الحبيبية، ونسبة الماء إلى الأسمنت، وطرق الخلط، ودرجة الحرارة، ومعدل القص، والضغط، والسلوك الانسيابي للأسمنت مع خبث افران الصهر الحبيبية. يؤدي زيادة خبث افران الصهر الحبيبية إلى زيادة في القص والضغط. تشير النتائج إلى أن زيادة الاستبدال الجزئي للأسمنت بخبث افران الصهر الحبيبية عند النسبة المثوية المثلى لاستبدال 45%، تليها انخفاض لاحق في اللزوجة البلاستيكية وإجهاد الخضوع حتى الوصول إلى نسبة استبدال 75.

1. Introduction

Given that concrete is a fundamental building material, the growing global needs have resulted in a rise in cement manufacturing and thus, unwelcome increases in CO₂ emissions. Consequently, the industry has placed significant emphasis on including a variety of recyclable components or by-products. These resources may be utilized as partial substitutes for cement in concrete manufacturing, thereby offering important environmental, economic, and technical advantages. GGBS is a frequently encountered by-product that may serve as a substitute for cement. Ground-grained blast furnace slag (GGBS) is a residual material produced during the smelting process of iron ore to pig iron. Great amount of GGBS are produced from foundries and steel works [1]. It exhibits a high degree of cementitiousness, which increases the durability and strength of the pavement [2, 3]. Cementing casing is a crucial stage in the drilling and completion of gas and oil wells, involving engineering and scientific disciplines [4, 5]. It involves placing a cement slurry in the annulus between the well casing and geological formations to create a solid mass for supporting and sealing [6]. The flow properties of oil well cement slurries impact the key task of cementing oil wells. To assess the mix-ability and pump-ability of OWC slurry, optimise mud removal and slurry placement, and forecast the impact of wellbore heat on slurry placement, a basic understanding of the rheology of Oil Well Cement slurry (OWC) is essential [7]. The cement rheology slurries is intricate due to the presence of many complicated interactions among the cement particles, water, other components, time, and temperature. Cement slurries are visco-plastic substances that display a yield stress. When the yield stress is below or equal to the yield stress, the slurry becomes a stiff solid. The yield point is a measurement of the attractive forces, (resulting from negative and positive charges located on or near the particle surface [8]). In order to analyse the flow properties of cement slurry, it is necessary to investigate rheological characteristics including yield stress, shear thinning, plastic viscosity, apparent viscosity and shear thickening behaviour. The rheological characteristics of cement slurries are described extensively using model of Bingham plastic and the Power law [9]. When shear rates are finite, model of Bingham plastic involve both yield stress and a limiting viscosity. A material's yield stress is the least force required for it to initiate motion and is determined

by the point where the flow curve intersects with the shear stress axis. Materials exhibit solid behaviour when their yield stress is below that threshold. In other words, yield stress is the result of friction between solid particles, namely the skeleton contribution [10]. According to a studied conducted by [11], fresh cement pastes exhibit at least two critical strains. The largest critical strain is attributed to the disruption of the colloidal interactions network among cement particles, which occurs shortly after the mixing process is completed. The smallest critical strain is linked to the deformation of the early hydrates, which primarily form at the contact sites between flocculated cement grains. Based on dimensional analysis, the research indicates that the mixture yield stress when it is not in motion may be estimated as a linear function of time [12]. Flow after initiation is governed by plastic viscosity, which is the contribution of suspended liquids coming from viscous dissipation caused by the movement of water in the sheared material. The plastic viscosity is the gradient of the linear regression line of the flow curve. Typically, the plastic viscosity of cement slurry is determined by analysing the linear section of the downward slope of the hysteresis loop. The down-curve was selected because of its superior fit to the Bingham plastic model compared to the up-curve. Typically, the down-curve exhibits lower shear stress values compared to the up-curve because of the structural breakdown in the slurry caused by shear flow [13]. Adding foam to the cement showed a notable increase in plastic viscosity as foam quality increased, foam quality impacted yield points because it showed a slight increase as foam quality increased [14]. Supplementary cementitious substances impact the rheological characteristics of cement in a similar manner. By virtue of its spherical particle form, fly ash (FA) decreases the water need when used as a partial substitute for cement. In contrast, silica fume (SF) leads to an increase in water demand by absorbing water because of its very large surface area. Rheological characteristics may vary in magnitude based on factors such as cement type, time and temperature, admixture, particle shape and type, replacement level, size distribution and loss on ignition of the utilised supplementary cementitious materials (SCMs). One argument is that there is a certain level of SF partial substitution for cement, over which both the plastic viscosity of concrete and the yield stress rise as the SF content increases [15]. [16] noted that the yield stress rose until reaching a 20% replacement level of small-firing (SF) and thereafter began to decline. A reduction in plastic viscosity was seen up to 10% SF, after which it began to rise at greater SF concentrations. [17, 18] observed that both the plastic viscosity and yield stress showed significant increases when the condensed SF content increased up to a threshold of 15% replacement. Differential properties of cementitious pastes, grouts, or suspensions based on interaction energy, particle size, and solid volume percentage. The model takes into consideration microstructural characteristics such as volume percentage of particle size, solids,

max packing, distribution of the distribution of particle sizes, inter-particle forces and percolation threshold, and in order to forecast the yield stress of particle suspensions [19]. The model for viscosity as a function of the solvent viscosity, the volume percentage of particles, and the maximum packing parameter was created by Krieger and Dougherty [20]. Several studies for examples [21, 22, 23 ,24, 11,25 and 26] used statistical techniques to choose the proportioning of mixtures for cementitious systems. A factorial design of experiments was used by [27] to assess the impact of human hair fibres on the mitigation of shrinkage cracking in mortar. The design elements taken into account were the cement/sand ratio, water/cement ratio, and human hair fibres content. These statistical approaches provide enhanced efficiency and reliability in the acquired data, and have the potential to optimise the tested systems with a reduced number of tests. A new concrete rheometer is introduced, detailing its innovations, design, operating principles, calibration, and reliability. A modified version of the Tattersall two-point device has been developed [28]. This work examines the rheological characteristics of oil well cement slurry with partial replacement of GGBFS at variable percentages (15-75%).

2. Material and Methods

2.1. Materials

This analysis utilizes [29] class G cement and GGBFS. Table (1) shows cement and GGBFS chemical compositions. Table (2) shows the material composition of cement, which meets [29] standards for class G cement "C₃S 65%, C₃A 3.0%, SO₃ 3.0%." (C989/C989M-18a- 2018) [30] was used to test GGBFS powder.

Table (1): Chemical Composition of Cement and GGBFS (%).

Compositions	Cement type G according to API	GGBFS
Calcium oxide (CaO)	64.20	36.44
Silica (SiO ₂)	21.60	31.76
Aluminum oxide (Al ₂ O ₃)	3.30	9.08
Iron oxide (Fe ₂ O ₃)	4.90	0.60
Sulfur trioxide (SO ₃)	2.20	0.97
Magnesium oxide (MgO)	1.10	7.51
Phosphorus pentoxide (P ₂ O ₅)	2.1	0.15
Loss on ignition	0.60	0.45

Table (2): Mineral Compositions of Cement (%).

Mineral compositions (%)	C ₃ S	C ₂ S	C ₂ F	C ₃ A	SO ₃
Cement Type G according to API	62	15	16	<1	2.2

GGBFS has the same chemical composition as standard Portland cement OPC (primarily SiO₂, CaO, Al₂O₃, and MgO) and is directly used in cement additives at 6-95% rates [5]. All patterns in flow behavior cannot be captured by a single rheological model [31]. Calculations are challenging because the performance of models changes with test geometries, shear gaps, and friction capacities [32]. The rate and stress of the shear, and viscosity data may be fitted to specific patterns using the time-independent rheological models that are now available. No model is faultless. Describes the rheology of cement slurries using the power law and the model of Bingham plastic [7]. Fluid flow and deformation are investigated through rheology [33], it defines the link between flow rate and pressure that result in movement [34] at limited shear speeds, the yield stress (γ) and limiting viscosity (p) of the Bingham plastic model are present. Using the Bingham plastic model, the shear rate-shear stress down-curve was used to calculate the plastic viscosity and yield stress Eq.1.

$$\tau = \tau\gamma + \mu p \quad (1)$$

τ = shear stress, $\tau\gamma$ = yield stress, p = plastic viscosity, and μ = shear rate, respectively. Down-curve [35].

2.2. Method and Procedure

In this paper, cement is altered by GGBFS with (15-75) % by weight with an interval of 15%. Preparation of the cement slurry was done according to API [29]; the test of slump flow is the most commonly used to estimate the horizontal flow (filling ability), and was carried out according to ASTM C-1437 [36]. The acceptance criteria of this test in oil well cement slurry is between (380-390) mm, according to the (American Petroleum Institute) (API) [29]. Starting from equivalent flow for cement slurry type G used 44%, water by weight of cement is 830 mm. using high-speed shear blende. The needed amount of liquid additive was first added to the water in the blender cup using a needle. The motor was switched on and kept at 4000 rpm (plus or minus 250 rpm) while the cement and GGBFS were added at a constant pace for no more than 15 seconds. Place the lid on the mixing container after 15 seconds of mixing at 4000 rpm and ± 250 rpm, and continue mixing for 35 seconds at 12,000 rpm and ± 500 rpm for a 1-liter container. During the thickening stage of the test, slurry is subjected to mixing energy for a proportion of the entire task duration. Shear rate affects slurry

during pumping. Slurry was blended according to API [29] to avoid concealing the impact of the wellbore shear rate, as shown in Figure (1).



Fig. (1): High-Speed Shear Blender

The procedure for rheology characterization using the cylinder viscometer is listed in full in API [37]. In order to test the slurry, the fluid is rotated at the lowest speed of 10 seconds, the corresponding torque reading is recorded, and all the remaining readings are recorded in ascending and descending order with 10 seconds of rotation at each speed. This method is known as the hysteresis loop. The sample is prepared in Table (3).

Table (3): Meaning of Symbol

Symbol ID	Cement (%)	GGBFS (%)	Mean of Sample ID	Yield Stress	Plastic Viscosity
W0	100	0	W refer to the specimen. The digit stands for percentage of 0% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model
W1	%75	15%	W refer to the specimen. The digit stands for percentage of 15% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model

W2	70%	30%	W refer to the specimen. The digit stands for percentage of 30% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model
W3	65%	45%	W refer to the specimen. The digit stands for percentage of 45% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model
W4	40%	60%	W refer to the specimen. The digit stands for percentage of 60% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model
W5	15%	75%	W refer to the specimen. The digit stands for percentage of 75% GGBFS replaced in cement	By using Bingham plastic model	By using Bingham plastic model

2.3. Experimental Work

Oil well cement (OWC) slurries' rheology impacts initial cementing. Fundamental knowledge of OWC slurry's rheology is important to the pump-ability and the mix-ability of the slurry evaluation, slurry placement and optimize mud removal, and estimate the effect of temperature of the wellbore on slurry placement. Fluid flow and deformation are investigated via rheology [38]. It defines the link between flow rate and pressure that generates movement [34]. The Model 800 8-Speed Electronic Oilfield Viscometer is the equipment for rheological properties evaluation in this investigation. It is utilized globally in the field and lab to accurately measure the rheological parameters of drilling fluids and cement as shown in Figures (2) and (3).



Fig. (2): Electronic Oilfield Viscometer

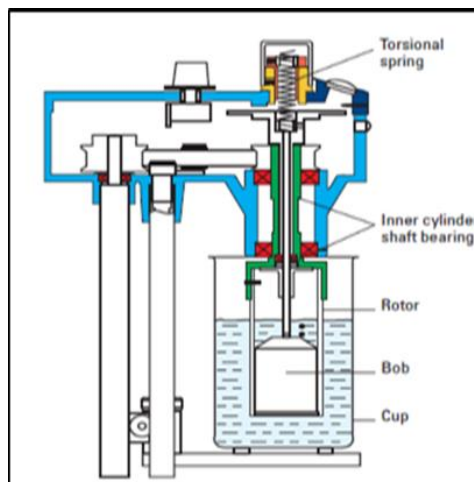


Fig. (3): Viscometer

3. Results and Discussion

The results of plastic viscosity and yield point of unblended and blended cement replaced with GGBFS tested according to API [37], are show in Table (4).

Table (4): Rheological Properties

Mix Symbols	W0 0%	W1 15%	W2 30%	W3 45%	W4 60%	W5 75%
RPM	Dial Reading	Dial Reading	Dial Reading	Dial Reading	Dial Reading	Dial Reading
Ø600	82.5	89	87	84	80	78
Ø300	70	64.5	63	60	57	55
Ø200	55	55	56	53	49	47
Ø100	46	46	44	41	38	36
Ø60	41.5	40.5	39	37	33	31
Ø30	37	36	35	32	28	26
Ø6	24	20	18	16	14	13
Gel0	20	17	18	15	14	13
Gel10	23	22	20	18	15	14
Plastic viscosity	12.5	24.5	24	24	23	23
yield Point	57.5	40	39	36	34	32

The behavior of cement with GGBS replacement indicates that, the plastic viscosity of blended cement with 15% percent of replacement of GGBS increased compared with unblended cement approximately with 48% high plastic viscosity of blended cement decreases 15% for all percent of replacement compared with blended cement. GGBS effect of GGBS on the specimen plastic

viscosity of blended cement with 75% approximately lower 6 % compared to blended cement of 15% as shown in Figure (4).

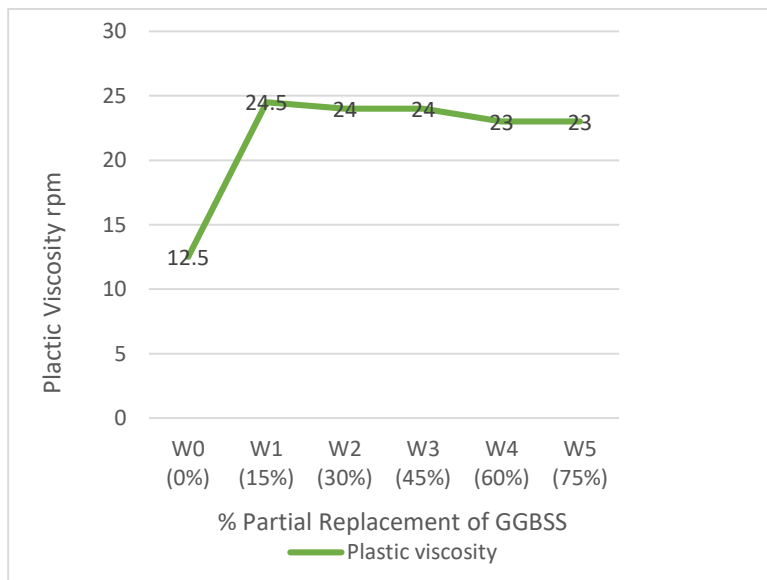


Fig. (4): Plastic viscosity

The results show that the yield point decrease for all percent of replacement compared with unblended cement because of the pozzolanic reaction with the calcium hydroxide released during cement hydration. This reaction consumes calcium hydroxide, leading to a reduction in the overall strength and stiffness of the concrete matrix. As a result, the yield point decreases. . The effect GGBS on the yield point of specimen of blended cement with 75% approximately lower 44% to unblended cement as shown in Figure (5).

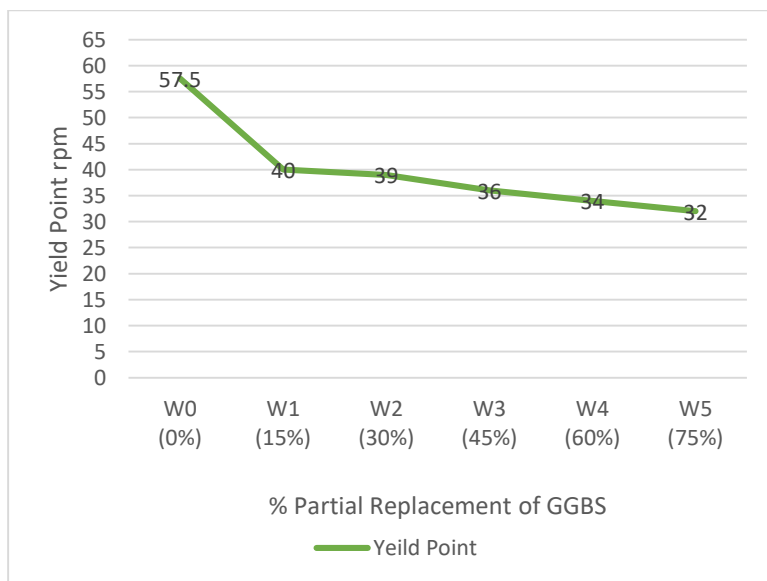


Fig. (5): Yield point

The results show that the Bingham plastic fluid model acts as Newtonian behavior, the relationship between the shear rate and the shear stress. At the high point of shear rate, the plastic viscosity is low, and that helps the slurries to reduce the circulation pressure and pressure losses and makes turbulent flow; in the low point of shear rate, the plastic viscosity is high, and that helps the slurries to displacement the mud as shown in Figure (6).

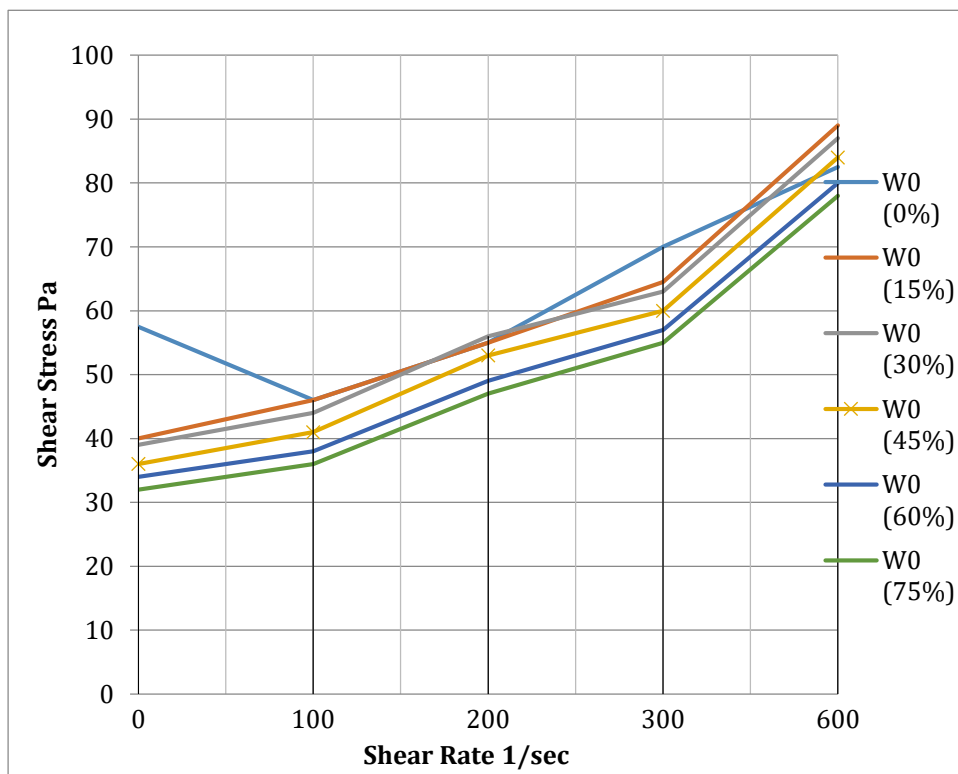


Fig. (6): Relationship between rate of the shear and stress of the shear (Bingham plastic fluid)

4. Conclusions

1. As expected, the OWC slurries plastic viscosity increased at replacement 15% by 48% compared with unblended cement, and decreased with increase the replacement.
2. The OWC slurries yield point decreased for all percent of replacement and at replacement of 75%, approximately with 44% lower than unblended cement.
3. The Bingham plastic fluid model acts as Newtonian behavior, the relationship between the shear rate and the shear stress. At the high point of shear rate, the plastic viscosity is low, and that helps the slurries to reduce the circulation pressure and pressure losses and makes turbulent flow; in the low point of shear rate, the plastic viscosity is high, and that helps the slurries to displacement the mud.

4. Results of the current work are valid for the used cement, while the other cement showed many characteristics.

Abbreviations and acronyms

Symbol	Description	Symbol	Description
γ	shear rate	Fe ₂ O ₃	Iron oxide
μp	plastic viscosity	G	Type of cement
τ	shear stress	GGBS	Ground-grained blast furnace slag
τy	yield stress	MgO	Magnesium oxide
Al ₂ O ₃	Aluminum oxide	mm	milli meter
API	American Petroleum Institute	MnO	Manganese oxide
ASTM	American Society for Testing and Materials	OWC	Oil well cement
C ₂ F	Dicalcium ferrite	P ₂ O ₅	Phosphorus pentoxide
C ₂ S	Di-calcium silicate	rpm	Revolutions per minute
C ₃ A	Tricalcium aluminate	SCMs	supplementary cementitious materials
C ₃ S	Tricalcium Silica	SF	silica fume
CaO	Calcium oxide	SiO ₂	Silica
CO ₂	Carbon Dioxide	SO ₃	Sulfur trioxide
FA	fly ash		

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