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Mixing energy of Well Cements: the gap between laboratory testing and field job

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Abstract

Previous review of cement mixing energy for oil and gas applications shows dual importance of mixing energy and shear rate. The slurry mixing conditions and energy strongly impacts the behavior of slurry. Often it is assumed that properties of cement obtained from laboratory testing correlate well with field mixing conditions. However, the field procedures are conducted in much lower shear rate compared to laboratory mixing procedures.

In this study, a comparison of cement properties such as cement strength (UCS) and rheology is compared with properties of same cement mixed with field mixer. Samples prepared in laboratory were mixed according to API standards at 4000 and 9000 rpms respectively. Samples prepared in field mixer were prepared under 2000 rpm using field type propeller and mixing container.

Our results show different results in measured properties when mixed in laboratory and field conditions. Our observations from these tests show that mixing energy is a poor concept to be used for achieving identical cement properties. Cement properties are impacted by different factors in addition to mixing energy

Introduction

The objective of a well cementing operation is to achieve zonal isolation in order to restrict the movement of fluids and gases from one zone to another zone; and to bond and support the well casing at each interval. In recent years, the number of problems with well cement has been reported worldwide. Numerous papers have been written in the literature discussing potential problems and challenges for achieving an effective isolation. These include cementing challenges in highly deviated wells, deepwater offshore basins, HPHT wells, annular pressure build up, gas migration, and contamination and cement shrinkage in downhole environments (Sabins, 1990, Ravi et al., 1999, Sweatman, 2000, Stiles and Hollies, 2002, Rusch et al., 2004, Duan & Wojtanowicz, 2005, Cowan, 2007).

Debonding problems and ineffective zonal isolation and/or a weak bond between the casing and the cement sheath and the cement sheath and formation may lead to short and long term leakage pathways (Teodoriu et al., 2013). In addition, stress cracking through the well's life is another concern for wellbore cements. Since, several pressure and thermal loads are applied in a typical well, cement needs to withstand all these load through time. These indicate importance of an optimum cement design for each downhole application. The design includes rheological properties, thickening time, fluid loss, strength, and other mechanical and chemical properties.

There are often challenges in obtaining good zonal isolation with cement. In downhole conditions wellbore cement integrity is compromised with time. Other problems include mechanical failure, chemical attacks, durability issues, sustained casing pressure, shrinkage and leakage. Poor cement-formation bond may arise as a result of mud cake which compromises the purpose of well cement integrity. In the downhole environment, cement undergoes reduction in strength (strength retrogression) with time as it is exposed to high temperature and pressure. Such situation usually creates a loss of zonal isolation which eventually affects the life span of wellbore (Gibson et al. 2011). It is often a challenge to obtain a good isolation at high pressure and temperature. Pressure and thermal dynamic loads occur during well's life are other factors triggering wellbore integrity problems (Teodoriu et al., 2010). Furthermore, cement is affected at high temperatures and pressures where its calcium silicate hydrate phase decomposes to alpha dicalcium silicate hydrate phase.

Sustained casing pressure is a critical problem in oilwell cementing. Rocha-Valadez et al. (2014) discussed the issue of sustained casing pressure in their research where data were analyzed and modeled for qualitative analysis of sustained casing pressure. Sustained casing pressure occurs when pressure regenerates in the well after the pressure has been released. Poor bonding between cement and casing or between cement and formation gives rise to gas leakage which can eventually cause sustained casing pressure. During hydrocarbon production, wellbore safety is affected by sustained casing pressure. At high temperatures, cement usually breaks down and thereby giving rise to leakage.

Another issue that should be taken into consideration is the centralization of the casing string. If the string of casing is not centralized in the wellbore, the cement will flow into the areas that provide the lowest amount of resistance. This path the flow takes is typically up the wider sides and this will result in areas that have no cement in them at all. Taking the path of least resistance known as Channeling. In order to keep this from happening, mechanical centralizers should be used in order to keep issues like this from happening. This is especially important in the Macondo well (Chief Counsel's Report. (2011), where their design called for a specific type and number of centralizers, and in this case, the incorrect centralizer and a lower number of centralizers were used.

In addition to discussed problems, properties of the mixed cement in the field often is not what observed in the laboratory which indicates mixing as another key factor that needs further research and consideration.

Mixing condition for cement slurries and how it impacts its properties is of great importance which often been ignored in the cement design. Typical cement slurry properties such as basic rheology, thickening time, compressive strength, shear strength and fluid loss can be directly impacted when mixing conditions change. Furthermore, mixing equipment and laboratory conditions are the other conditions rarely investigated. Although API standards govern the mixing procedures for oilwell cements, it is either difficult to follow specifics in field conditions or sometimes it is great challenge to keep consistent mixing procedures from one laboratory procedure to another.

Cement and Wellbore Integrity

Several factors can trigger short and long integrity of the wellbore systems. These include type of the cement, cement design, well type, completion method, cement plug type if abandoned, abandonment method, geology, well age and especially cyclic pressure and thermal loading in the well's life (Nygaard et al., 2011, Watson and Bachu, 2009). In addition, the techniques used for completions and abandonment vary from wellbore to wellbore and different wells may be completed and/or abandoned at different intervals.

Generally, the leakage problem in the wellbore can be classified into two categories (Figure 1). The primary risks are more related to poor cement job and the secondary category is more related to the chemical reactions and tensile stresses occurring in the cement.

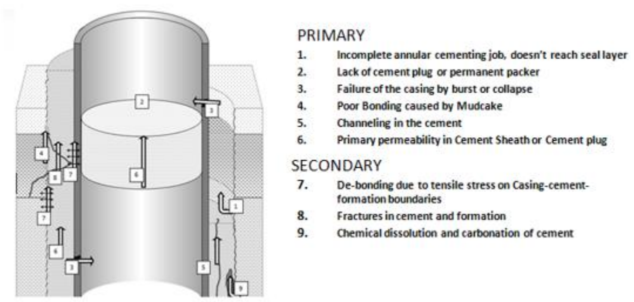

Figure 1. Potential leakage pathways (modified from Celia, 2004)

Different well types, as well as the current status of a well, give rise to different potential leakage scenarios. In the case of an exploration well, the main section of the hole is drilled and not cased. After the well is abandoned, cement plugs are usually set across any porous formations. A well that is drilled and abandoned without setting a production casing can leak natural gas at the cement/rock interface or through the cement plug if it is not properly set. Cement plugs may also be misplaced or missing. For a production well, a production casing is placed down to the production zone of interest and cemented in place. The cement sheath for cased wells is thin compared with the abandonment plugs because the thickness of the cement is limited to the annular space between the casing and the rock formation. Cased wells may also have casing exposed directly to the formation because the casing is not always cemented to the surface. When cased wells are abandoned after production or injection, a cement plug is set over the producing interval or the well is plugged with a bridge plug with or without a cement plug on top. The cased well with a short cemented interval inside the casing represents another leakage pathway. In a well cased to total well depth, gas can leak along the interfaces between different materials, such as casing/cement/rock interfaces, and through cement or fractures in the cement. In addition to these smaller-scale features, leakage can occur where the wells are cemented only over a short interval or the cement sheath is not uniformly covering the entire well circumference.

Even after a successful cement sheath is created, the integrity of the well can be compromised by secondary sources (see Fig. 1). One mechanism is failures caused by mechanical (pressure) and thermal loads imposed on the well. These loads can create the potential for tensile and shear failures in the casing/cement/formation boundaries or inside each of those elements. Changing fluid density for completion and stimulation can also induce mechanical loads on the inside of the casing, which requires consideration for integrity evaluation. Changes in temperature as a result of injection, or reheating of the wellbore during well shut-ins can impose thermal stresses. Temperature changes in geothermal wells have been noted to cause long-term well-integrity problems by creating fractures and fissures in the cement (Milestone and Aldridge 1990; Shen and Pye 1989). Furthermore, corrosion in the casing or chemical reactions of the cement can also create near-wellbore leakage pathways (Fig. 1). All of these leakage pathways compromise the wellbore integrity and can allow fluid to flow into the annulus or the wellbore.

In addition to the influences of well construction, the chemical and geochemical effects of the gas on well integrity and temperature and pressure changes in the wellbore can also change the integrity of the wellbore. Randhol and Cerasi (2009) provide a review of the mechanical factors than can influence the wellbore cement-sheath integrity. They pointed out that fractures in the cement sheath can occur from de-bonding of cement and fracturing at the rock formation interface caused by the different water activity in the shale and the cement. If filter cake of the mud is not properly removed, channeling of the cement can occur. During injection temperature and pressure changes will lead to stress exposure in the injection wells which conventional class G cement is not suited (Pederson et al., 2006).

One challenge regarding wellbore integrity is the existing standards for well construction, including tubular casing and cement (Sakmaier et al, 2017). These standards need to be improved in relation to long-integrity testing and temperature and pressure effects. For instance, the petroleum industry does not perform long-term integrity testing for permanent well barrier elements such as cement, casing, and plugging materials (Vignes, 2011). In addition, those tests do not include exposure to gas as test medium (Vignes, 2011). As a result, companies in the cement industry use different procedures to ensure the long term integrity of the cement.

Cement Mixing Energy Concept

Mixing condition for cement slurries and how it impacts its properties is of great importance which often been ignored in the cement design. Typical cement slurry properties such as basic rheology, thickening time, compressive strength, shear strength and fluid loss can be directly impacted when mixing conditions change. Furthermore, mixing equipment and laboratory conditions are the other conditions rarely investigated. Although API standards govern the mixing procedures for oilwell cements, it is either difficult to follow specifics in field conditions or sometimes it is great challenge to keep consistent mixing procedures from one laboratory procedure to another.

A theory for mixing energy was developed and proposed by Oraban in 1986 (Orban et al., 1986). It was further used and emphasized in others work such as Hibbert et al., 1995 and Vidick et al., 1990. Initial effects of mixing energy on cement slurry are first evaluated by conducting rheological measurements according to API 10A specifications. The Bingham rheological model was used to describe the results. The popular formula of mixing energy developed and presented as:

$$\frac{E}{M} = \frac{k \times \rho \times \omega^2 \times t}{\rho \times V} = \frac{k \times \omega^2 \times t}{V} \quad \text{.......(1)}$$

Based on this equation, mixing energy (E/M) has direct relationship with shear rate (ω), mixing time (t) and inversely related to volume. k was experimentally found to be 6.4 10^{-9} N.m/kg.m^{-3}/rpm.

The major application of this theory was to have consistent properties for the slurry mixtures with same mixing energies prepared in laboratory and field. Orban et al, 1986 further showed that the properties of cement slurries such as rheology, fluid loss and strength change with intensity of mixing. He further related this to the deflocculation process in which mechanical stresses during mixing process are found to be critical.

Although, Orban's work was the ground breaking in acknowledging mixing energy concept, some others were in disagreement with the concept and application of this theory. For instance, Padget 1996 highlighted importance of shear rate as a phenomenon impacting properties rather than mixing energy. He showed laboratory experiments and field observations highlighting effects of shear rate of the mixing system rather than the total energy. He further showed that slurries prepared under high shear rate may have different properties compared to slurries prepared in low shear rate. In addition, his results showed some cement properties such as rheology, free water and thickening time change by mixing intensity only for some of the prepared samples. Furthermore, his data thickening time slightly affected by the mixing energy (Figure 2).

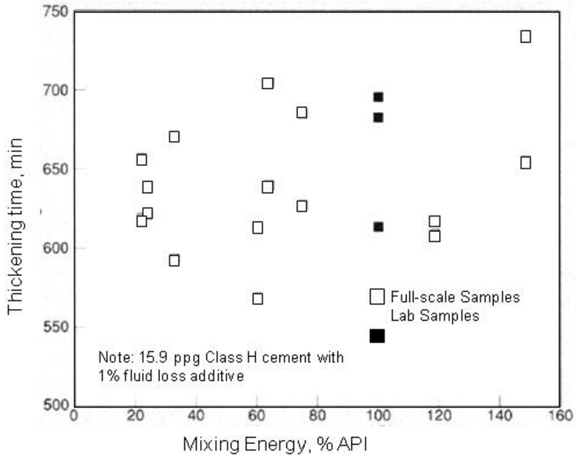

Figure 2. Thickening time vs. mixing energy (Padget et al., 1996). Thickening time results slightly responsive to mixing energy

Furthermore, it was observed that the properties changed more significantly when different mixing equipment were used rather than differences between the mixing energies. This was more appear for free water results which was higher in the field conditions compared to laboratory tests. Furthermore, it was found that compressive strength is not function of mixing energy. His work concluded limited application of mixing energy concept. These results were contradicting Orban's work published earlier on 1986. Padget explained differences in laboratory and field results due to extremely different shear rates in laboratory equipment and field conditions. Where the shear rate of centrifugal pumps on the operational conditions generally less than 2,000 Sec^{-1} whereas the laboratory equipment relying on API standards generates more than 30,000 Sec^{-1}. He further recommended a new equation for mixing energy which is directly related to the shear rate as:

$$\frac{E}{M} = \mu \times t \times \gamma \quad \text{............(2)}$$

Where μ is the viscosity and γ is the shear rate. The concluding remark from using this new equation according to Padget is "if *the residence time is increased, a low shear device (jet mixer, batch mixer) can exert same amount of mixing energy into a slurry as a high-shear device (laboratory blender). However, because it is shear rate that is more important, the properties will not necessarily be the same*"

Alternatively, another equation is provided for mixing energy based on the cement slurries during field scale mixing equipment. The equation is developed based on summing the mechanical work provided by flow through mixing and pumping system (Viddick et al., 1990, Hibbert et al., 1995)

$$\frac{E}{M} = \sum \frac{P \times t}{\rho \times V} \times 2.35 \left(\frac{kJ}{kg}\right) \quad \text{........................(3)}$$

Where

P is the power in horsepower
T is the residence time of slurry in the mixing device (min)
V is the volume (bbl)
ρ is the density (lb/gal)
2.35 is the conversion factor to kJ/kg

Saleh and Teodoriu, 2017 previously presented a review of mixing energy theory and applications in other industries. In a recent study, Saleh et al., 2018 shows how mixing water can also impact important cement properties such as thickening time, rheology and strength.

Experimental Design

One objective of experimental design in this work is to investigate how changing mixing energy and shear rate will impact cement properties. The methodology of mixing is composed of single step and two step procedures (API mixing procedure). In single step mixing, only one shear rate is considered and mixing time is calculated using mixing energy theory formula presented previously.
In two step API recommended procedure, mixing time was calculated based on 4000 and 12000 rpm using the same formula. Calculated mixing time for all the experiments are reported in the Table 1.
The original DoE for single step mixing has two factors three level analysis (3^2). Two factors considered are mixing energy and shear rate. This design considered three shear rates at 6000 rpm, at 12000 rpm and at one mid-point of 9000 rpm. API mixing procedure recommends mixing at 4000 rpm and 12,000 rpm. Therefore, upper limit of 12,000 rpm was considered in the experimental design, 6000 rpm (half of upper limit) was considered as lower limit for shear rates in the experimental design.

Table 1. Calculated mixing time using mixing energy formula

Mixing Energy Level (KJ/Kg)	RPM	Mixing Time (Sec)
5.9	6000	147
5.9	9000	65
5.9	12000	37
8.9	6000	222
8.9	9000	99
8.9	12000	56
11.8	6000	294
11.8	9000	131
11.8	12000	73

Sample Preparation and Compressive Strength Tests

Before conducting compressive strength tests, cement specimens were mixed according to mixing conditions designed in this work. In each time, cement slurry was poured into 2 inch by 2-inch cement molds and left to cure in a water bath for one, three and seven and twenty-one days (Fig.3). On each specific test day, samples were removed from the molds and used in testing.
The unconfined compressive strength (UCS), also known as the uniaxial compressive strength, is a measure of a material's strength. This is a very important property of cement. Weak cement slurries (low UCS) can create severe wellbore integrity issues throughout the life of the well. Some minimum requirements for UCS are needed before moving forward with drilling operation for the next interval. There are two common methods to test for strength of cement, one is by conducting a crush test where only normal pressure is applied (no confining stress). Another way is a non-invasive method based on ultrasonic velocity. Using a crush test, UCS is defined as the maximum axial compressive stress that a sample of material can withstand under unconfined conditions – the confining stress is zero. In other words, it is the ability of a material to resist applied forces. A vertical stress is applied on the sample at a specific rate of increase until the sample fails. When the sample fails, σ_c (compressive strength) is equal to major principal stress (σ_1) which is defined as the maximum applied vertical stress divided by the cross-sectional area of the specimen at the maximum vertical stress:

$$\sigma_c = \frac{F}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Fig.4 shows a certified crush testing machine used for UCS testing. The device consists of a load frame and a digital indicator to measure the compressive strength. The load frame has a static steel block at the bottom and an upper block which can apply a load force in a downward direction. Compressive strength tests were performed one, three and seven, and twenty days after the slurry was mixed.

Figure 3. Cement specimens cured in water bath before being used for UCS testing

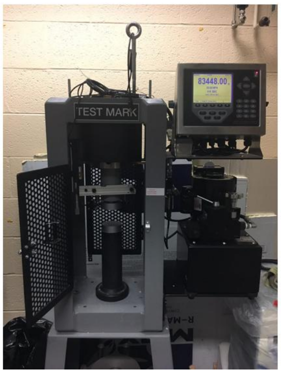

Figure 4. Certified crush test for UCS measurements

Testing Results

Here we report UCS results for testing proposed in Table 1. Total, 108 samples tested for proposed DoE in table 1. Total 36 samples tested for two step mixing procedure according to the API recommendations. All the UCS tests were conducted in 1, 3, 7 and 21 days. For each testing condition, three samples were used. All samples were made in identical conditions using neat class H cement from same batch. After mixing and pouring in molds, they were cured in deionized water. All the tests were conducted using same compression machine certified by API and ASTM. Results are first presented for each individual mixing energy and then compared for each specific curing time. Finally, ANOVA results are presented to investigate significance of each variable.

UCS Results for 5.9 KJ/Kg in the Laboratory

Results of UCS testing at 5.9 KJ/kg mixing level conditions are reported in Figure 5 for all mixing conditions and 1, 3, 7 and 21 curing days. Figure 5 indicates that, UCS values increasing by curing days which is consistent with previous results reported in the literature, as the cement cures, it gains strength. Results of 1 day curing indicates fluctuations in UCS values with different mixing condition. Cement goes under very active hydration process in the first day of curing which hinders effect of shear rate and mixing energy (Nelson and Gulliot, 2006). In three days curing time, it is evident that as the shear rate is increasing from 6000 rpm to 12,000 rpm, UCS values decline by about 29%. At 3 days curing, highest UCS at 6000 rpm mixing is 24.34 MPa and at 12,000 rpm mixing is 17.31 MPa. Lower shear rate will provide better mixing conditions where cement particles can better interact with water molecules. At 3 days curing time, UCS value for samples prepared based on API mixing conditions is 20.25 MPa. This value is by average 14% more than UCS value of samples prepared at 12,000 rpm and 16% less than UCS value of the samples prepared at 6000 rpms. This can be explained by having both low and high shear mixing conditions in preparation of API samples.

At 7 days curing, a similar trend is observed confirming higher UCS values at lower shear rate. At this curing time and 6000 rpm, UCS value is 35.64 MPa and drops to 34.3 MPa and 29.32 MPa, respectively at 9000 and 12000 rpm mixing conditions. This is a maximum drop of 22% between UCS of samples at 6000 and 12000 rpms which is lower than 29% drop observed at 3 days curing time data. UCS results for samples prepared at API mixing conditions after seven days curing is 29.96 MPa. This value is by average 2% more than the UCS value at 12000 rpm mixing condition at 7 days curing time and by average 16% less than the UCS value at 6000 rpm mixing condition.

Data for twenty-one days curing time confirms similar observations as for UCS values in three and seven days curing time. At this curing time and 6000 rpm, UCS value is 48.63 MPa and drops to 47.56 MPa and 38.4 MPa, respectively at 9000 and 12000 rpm mixing conditions. This is a maximum drop of 12% between UCS of samples at 6000 and 12000 rpms which is lower than 22% drop observed at 7 days curing time data. UCS results for samples prepared at API mixing conditions after 21 days curing is 42.95 MPa. This value is by average 10% more than the UCS value at 12000 rpm mixing condition at similar curing time and by average 13% less than the UCS value at 6000 rpm mixing condition. Overall, this data shows that shear rate plays an important role in cement mixing where even though mixing energy kept constant, UCS values are not similar. Furthermore, UCS value of the samples prepared at API mixing conditions is by average higher than UCS values of samples prepared at 12000 rpm mixing but less than the UCS value of the samples prepared at 6000 and 9000 rpms.

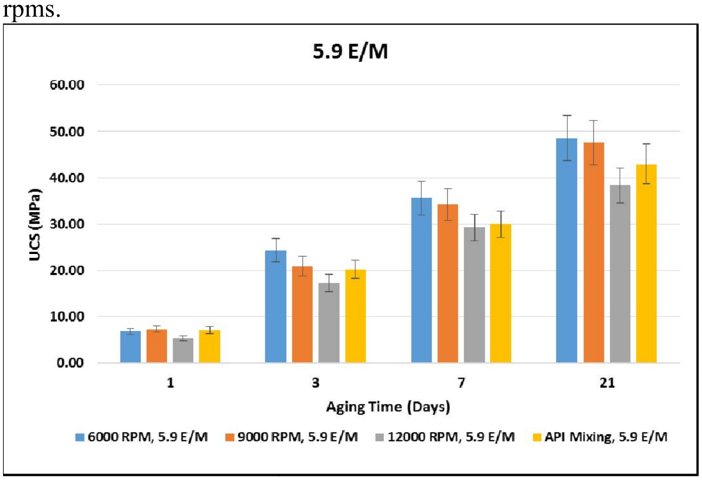

Figure 5. UCS test results for 5.9 KJ/Kg mixing energy levels at all shear rate conditions and API mixing procedures. Data indicates that shear rate and mixing time plays an important role in cement mixing where even though mixing energy kept constant, UCS values are not similar

Yard Mixing

The objective for using yard mixer was to compare laboratory results from API mixing condition at the laboratory to an experiment in larger scale similar to the field. Due to time consuming process involved with yard type mixer, it was a challenge to conduct more than one test. Another problem was that a larger volume required for mixing using big mixer. The primary objective for this comparison was to investigate whether or not cement properties will change if slurry is mixed with yard mixer by keeping mixing energy at the similar level as the slurry mixed in laboratory condition. For consistency with API recommended mixing energy, we used 5.9 E/M for mixing slurry using the big mixer. The mixer, propeller used inside drum and mixing baffle is illustrated in the Figure 7 and 8. Mixing baffles are usually embedded for increased turbulence and mixing quality. Due to geometry of drum, minimum volume required for proper mixing was calculated to be 36,000 ml (0.23 bbl). Mixing time was set to twenty minutes. After mixing process, samples were collected to perform UCS/UPV tests at similar curing conditions with the lab. In addition, samples from same batch were used for conducting rheology and thickening time tests. In order to keep the energy level constant at 5.9 E/M using the yard mixer, we used the horse power from the yard mixer (0.5 HP) and calculated the required mixing time to reach the 5.9 E/M energy using formula as presented in the literature. The equation is developed based on summing the mechanical work provided by flow through mixing and pumping system (Viddick et al., 1990, Hibbert et al., 1995)

Figure 7: Drum mixer was used to prepare and mix cement slurry at low rpm

Figure 8: Drum baffled container and propeller used for mixing

UCS Results from yard mixing and comparison to laboratory

Results of UCS testing at 5.9 KJ/kg mixing level condition are reported in Figure 9 for samples prepared at API and yard mixing conditions and in curing times of 1, 3, 7 and 21 days. Figure 9 indicates that, UCS values increasing by curing days which is consistent with previous results reported in the literature, as the cement cures, it gains strength. Results of first day curing indicates very small difference in values, with having sample prepared by yard mixer stronger by about 4%. In general, a trend of higher UCS values is observed for samples prepared using yard mixer. Results for 3 and 7 days curing show respectively 4% and 11% difference (higher in sample prepared using yard mixer). The higher strength using yard mixer can be explained due to very low rpm used (1800) and fairly longer mixing time (20 minutes versus 50 seconds). This provides more surface area for cement reaction which yields to higher strength values. Similar phenomenon observed when comparing results of samples prepared at 6000 rpm and API mixing condition. In 21 days curing, we observe more than 4% difference confirming similar trend in longer time. Based on these results, it can be cautiously concluded that cement UCS is not only function of mixing energy as per mixing energy theory but also function of other mixing conditions such as mixing time and shear rate and mixing equipment.

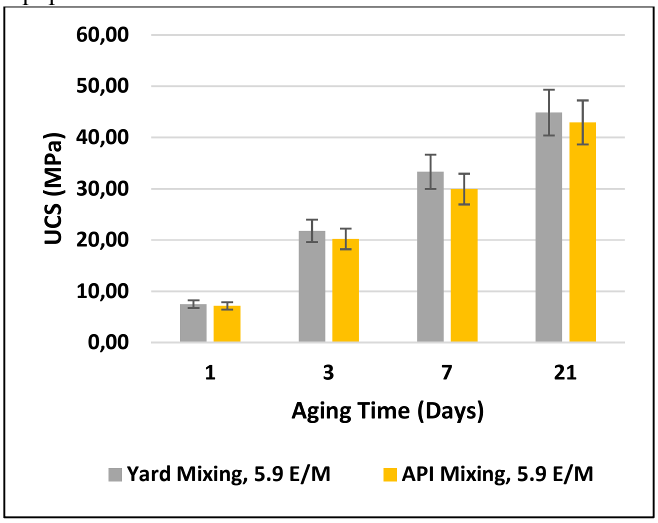

Figure 9. UCS test results for 5.9 KJ/Kg mixing energy levels for samples prepared by API mixing procedure and yard mixing procedure

Rheology comparison between laboratory and yard mixing

Test results for shear stress and shear rate of the slurry prepared at 5.9 KJ/Kg using laboratory and yard mixer is shown in the Figure 10. Test results indicate that higher shear stress is observed when comparing test results from laboratory mixer to yard mixer. In another word, sample becomes thicker using yard mixer even though both samples were prepared by 5.9 E/M mixing energy. Furthermore, results of PV and YP are shown in the Figures 11 and 12. As expected, we can observe higher PV and YP in slurries prepared by yard mixer. These measurements were consistent with visual observations of slurries mixed using yard mixer. As shown in the Figure 13, larger cement chunks were observed in the slurry mixed with yard mixer. As explained earlier, PV strongly correlates with size and shape of solids in addition to solids concentration. We can see that in yard mixing method, large solids are left inside therefore increasing PV. Similarly, YP is strongly correlated with surface properties of solids and their volume concentration, therefore, having larger solids left inside the mix has increased YP as well. This can be explained from deflocculation theory as well, where in yard mixing, due to poor deflocculation, larger particles were left.

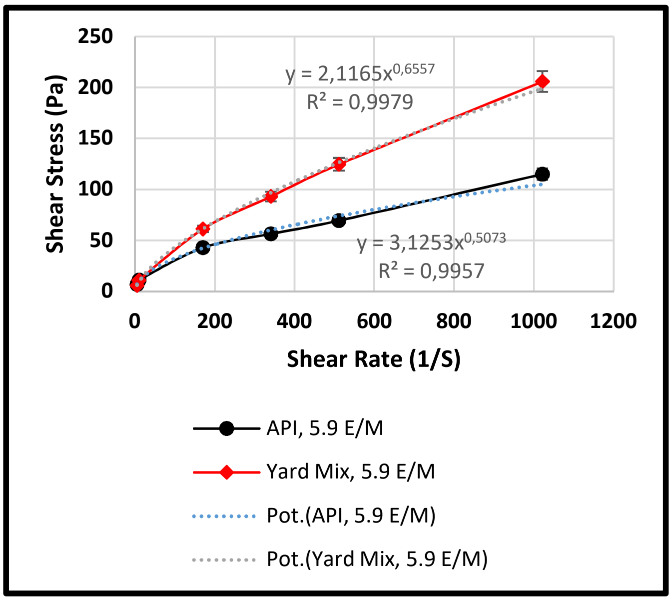

Figure 10. Rheology test results for 5.9 E/M and for slurries mixed using laboratory and yard mixers

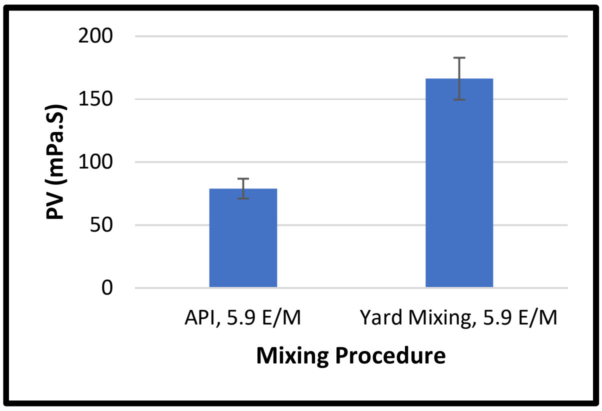

Figure 11. Calculated plastic viscosity (PV) for slurries mixed using laboratory and yard mixers

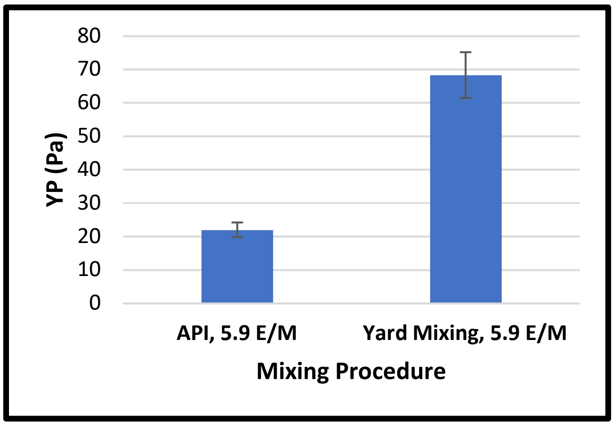

Figure 12. Calculated yield point (YP) for slurries mixed using laboratory and yard mixers

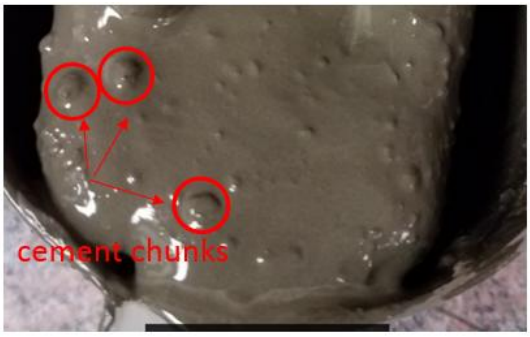

Figure 13. Cement chunks can be seen inside the slurry prepared using yard mixer

Conclusions

In this study we have compared results from mixing in the laboratory and yard type mixing. Mixing energy has been kept constant in all mixing condition. In the laboratory mixing, we have considered a two factors three levels (3^2) experimental design to investigate impact of shear rate on UCS of cement specimens. In addition, we have considered a methodology composed of single step and two step procedures (API mixing procedure). In single step mixing, only one shear rate is considered and mixing time is calculated using mixing energy theory formula.

Here a brief summary of UCS test results for different mixing energy and mixing conditions are reported:

1) There is a big difference in UCS data when comparing at different mixing condition in the laboratory. For instance, there is 40% difference observed in UCS data for one-day curing. UCS data

for one-day curing time has lowest value of 5.42 MPa prepared at 12000 rpm mixing for 5.9 E/M and maximum value of 9.08 MPa for 11.8 E/M prepared at 6000 rpm mixing.

2) UCS tests comparison between laboratory and yard mixing indicate slightly higher strength for the samples prepared using yard mixer (11% difference). This can be explained due to due to very low rpm used (1800) in the yard mixer and longer mixing time (20 minutes versus 50 seconds). This provides more surface area for cement reaction which yields to higher strength values.
3) Rheology tests indicate significantly higher rheology for the samples prepared using yard mixer. Up to 52% and 67% increase was observed in PV and YP, respectively. These results can be justified by observation of larger cement chunks in the slurry mixed with yard mixer.
4) Results from laboratory mixing indicate impact of shear rate where at higher mixing time (lower shear rate mixing) conditions (6000 rpm), higher UCS values achieved.
5) UPV results are not as sensitive as destructive UCS tests to changes in the mixing condition.
6) Keeping mixing energy constant will not yield in similar properties as outlined by mixing energy theory with some previous studies in the literature (Orban et al., 1986). Our data clearly shows that when mixing energy is kept constant, there is a considerable difference in the test data.

As it was observed in our experiments and yard mixing results, even though mixing energy was kept constant we observe a significant difference in some of the cement properties such as rheology. It is important to consider scale difference in terms of slurry mixing. Quantifying the mixing energy alone does not provide a robust basis to measure cement performance in the laboratory and the field.

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