Reducing the Waiting-On-Cement Time of Geopolymer Well Cement using Calcium Chloride (CaCl₂) as the Accelerator: Analysis of the Compressive Strength and Acoustic Impedance for Well Logging

Nurul Nazmin Zulkarnain 1,*, Syed Ahmad Farhan 2©, Yon Azwa Sazali 1, Nasir Shafiq 2©, Siti Humairah Abd Rahman 1, Afif Izwan Abd Hamid 2 and Mohd Firdaus Habarudin 1

1 PETRONAS Research Sdn. Bhd., Bandar Baru Bangi, Selangor 43000, Malaysia; yonazwa.sazali@petronas.com (Y.A.S.); humairah.rahman@petronas.com (S.H.A.R.); mfirdaus.habarudin@petronas.com (M.F.H.)
2 Institute of Self-Sustainable Building, Universiti Teknologi PETRONAS, Seri Iskandar, Perak 32610, Malaysia; syfarisk@gmail.com (S.A.F.); nasirshafiq@utp.edu.my (N.S.); afif_g03455@utp.edu.my (A.I.A.H.)

* Correspondence: nazmin.zulkarnain@petronas.com

Abstract: Geopolymer cement (GPC) is an aluminosilicate-based binder that is cost-effective and eco-friendly, with high compressive strength and resistance to acid attack. The effect of the concentration of calcium chloride (CaCl₂) as the accelerator on the compressive strength and acoustic impedance of GPC for well cement, while exposed to high pressure and high temperatures, is presented. Fly ash from the Tanjung Bin power plant, which is categorized as Class F fly ash according to ASTM C618-19, was selected as the aluminosilicate source for the GPC samples. Sodium hydroxide and sodium silicate were employed to activate the geopolymerization reaction of the aluminosilicate. Five samples with a density of 15 ppg were prepared with concentrations of CaCl₂ that varied from 1% to 4% by weight of cement. Findings revealed that the addition of 1% CaCl₂ is the optimum concentration for the curing conditions of 100 °C and 3000 psi for 48 h, which resulted in the highest compressive strength of the product. Results also indicate that GPC samples that contain CaCl₂ have a smaller range of acoustic impedance compared to that of ordinary Portland cement.

Keywords: accelerator; acoustic impedance; acoustic velocity; additive; calcium chloride; compressive strength; geopolymer cement; ordinary Portland cement; transit time; well cement

1. Introduction

The design and construction of the first carbon neutral building in Australia (the Global Change Institute building within the campus of the University of Queensland) in 2013 [1], and the largest geopolymer concrete project in the world (the Brisbane West Wellcamp airport—where heavy duty geopolymer concrete was used for pavement) in 2014 [2], are a testament to the growing interest and immense progress in geopolymer research since it was instigated in 1970 by Joseph Davidovits [3]. In addition, geopolymers have also been used in mainline railway sleepers and military airbases [4]. In the wake of the advancement of the applications of geopolymers in the construction industry, investigations into the potential application of geopolymers for well cement in the oil and gas industry, where geopolymer cement (GPC) is exposed to various conditions of the downhole environment, such as high pressure and high temperature (HPHT) conditions and the presence of carbon dioxide (CO₂), hydrogen sulfide (H₂S), brine and saline water, have been initiated.

GPC is an aluminosilicate-based binder that is cost-effective and eco-friendly, with a high compressive strength and resistance to acid attack [5]. Currently, ordinary Portland
cement (OPC) is the conventional well cement material [6]. The drawback of OPC is that it has a high calcium content of approximately 60%. The calcium ions may react with carbonic acid (H$_2$CO$_3$) to form calcium carbonate (CaCO$_3$). Subsequently, once the calcium ions in calcium-silicate-hydrate (C-S-H) are completely consumed, H$_2$CO$_3$ reacts with CaCO$_3$, which consequently increases the porosity and permeability of the cement, and thus leads to the reduction of the mechanical strength and integrity of the isolation barrier in the downhole environment. GPC can resist degradation when exposed to CO$_2$, by virtue of the low calcium content of the aluminosilicate source, and therefore has great potential to replace OPC as a well cement material, especially in CO$_2$-rich downhole environments that promote cement carbonation and degradation [6–9]. Moreover, in comparison to that of OPC, the manufacturing process of GPC is more energy-efficient [10] and cost-effective [11].

In the oil and gas industry, cement is pumped into the well to provide support to the casing as well as to isolate the casing from water and hydrocarbons in the pay zone. The placement of annular cement behind the casing is depicted in Figure 1. The volume of cement to be pumped has to be sufficient to reach the target-top. Once the cement is pumped to the desired depth, the cement must gain sufficient compressive strength, as set by the operating company, before drilling can commence for the following hole section. A non-destructive strength simulation may be conducted using the static gel strength analyzer to determine the waiting-on-cement (WOC) time required to achieve sufficient compressive strength.

![Figure 1. Schematic representation of the typical annular cement placement in the downhole environment.](image-url)
Once the minimum WOC time is reached, and, concomitantly, the cement has passed the weight and tag tests, the drilling of the following hole section can commence, as there is a possibility that the drilling bit might get stuck in the cement if drilling is conducted while the cement is still in the wet phase. However, if the WOC time is prolonged, the operating company has to pay unnecessary additional rig costs. Furthermore, the cement must have sufficient compressive strength prior to being perforated. The compressive strength of the set cement may be evaluated by performing cement bond logs. The tools employed to perform cement bond logs measure the loss of acoustic energy through the cement medium by propagating ultrasonic waves from the transmitter across the casing, cement, and formation, and then back to the signal receiver. The tools have to be calibrated prior to running the cement bond logs by tuning the acoustic impedance value to suit the expected type of fluid in the well. The acoustic impedance, $Z$, is expressed in MRayl and is the product of density ($\rho$) and acoustic velocity ($V$) as shown in Equation (1). The transit time ($\Delta t$) refers to the propagation of the ultrasonic wave from the transmitter transducer across the cement medium to the receiver transducer and is the reciprocal of $V$ as shown in Equation (2). Typical $\Delta t$ values for various materials are presented in Table 1 [12].

$$Z = \rho V$$

(1)

where the density ($\rho$) is expressed in kg/m$^3$ and the acoustic velocity ($V$) is expressed in m/s.

$$V = \frac{1}{\Delta t}$$

(2)

where the transit time ($\Delta t$) is expressed in $\mu$s/ft.

Table 1. Transit time ($\Delta t$) through various materials.

| Material        | $\Delta t$ (µs/ft) |
|-----------------|--------------------|
| Sandstone       | 55.5               |
| Limestone       | 47.6               |
| Dolomite        | 43.5               |
| Anhydrite       | 50.0               |
| Oil             | 222.0              |
| Steel Casing    | 57.0               |
| Mud             | 167.0              |
| Cement          | 90.0–160.0         |

Well cement is commonly mixed with additives, such as an accelerator, retarder, dispersant, fluid loss, and gas block, to ensure that the properties of the cement can withstand the harsh downhole environment and meet all of the standards set by the operating company. In cases where the well cement has to be pumped at higher depths under exposure to higher temperatures, employing retarders, such as, among others, borate salt, citric acid, lignosulfonate, phosphonate, and sugar, are recommended as one of the additives in the well cement to slow down the hydration rate and thus increase the thickening time. If the cement is too viscous, a dispersant can be added to the cement mixture to reduce the interfacial tension on the cement surface.

The application of GPC as the well cement material by substituting 100% of the OPC content has to be investigated in terms of the adaptability of the aluminosilicate source and alkaline activator towards the additives in the well cement, which were previously configured for OPC.

Common accelerators for well cement are composed of salt-based materials. They enhance the hydration rate of the cement, which results in the elevation of early compressive strength. Normally, the accelerator is used for the cement that is targeted at shallow depths. However, the application is still subjected to the temperature and pressure of the well. By
accelerating the hydration rate, the operating company can reduce the WOC time, which subsequently results in savings in the rig cost.

The adoption of calcium chloride (CaCl$_2$) as the accelerator has been considered in previous research for OPC. A previous study [12] investigated the effect of CaCl$_2$ on the compounds of OPC for 1, 7, and 28 days, and discovered that the addition of CaCl$_2$ to tricalcium silicate increased the cement strength for all durations, while the effect on dicalcium silicate on Day 1 was inappreciable. Meanwhile, the compressive strength of tricalcium aluminate increased on Day 1, but decreased on Day 7 and Day 28. The addition of 1% anhydrous CaCl$_2$ to the OPC mortar was found to demonstrate an approximately 100% higher strength compared to that of the plain mortar at Day 1 and a 15% higher strength at Year 1. In another study [13], it was observed that the addition of 4% of CaCl$_2$ to three different types of OPC increased the compressive strength of concrete, which was cured at 7, 14, 21, and 28 days. Similarly, another study [14] revealed that as the concentration of CaCl$_2$ increased from 1% to 2%, the compressive strength of the OPC concrete also increased for curing durations of 1, 3, and 7 days. However, at Days 28 and 90, the cement samples gained the highest compressive strength at a CaCl$_2$ concentration of 1.5%, and the compressive strength decreased as the concentration of CaCl$_2$ increased to 2%. The increase in compressive strength of the OPC with the addition of CaCl$_2$ is discussed thoroughly by another study [15] through a calorimetric study and thermodynamic modelling, and it was revealed that the CaCl$_2$ resulted in a higher supersaturation of C-S-H, which reduced the free energy barrier and consequently enhanced the nuclei formation on the cement surface.

Research on the adoption of CaCl$_2$ as the accelerator for GPC for well cement is scarce. A previous study [16] discovered that GPC with 1% CaCl$_2$ has a higher compressive strength compared to that with 2% CaCl$_2$. In addition, geogrid reinforced concrete showed the highest compressive strength at a CaCl$_2$ concentration of 0.5%, and the compressive strength decreased by approximately 4% as the concentration of CaCl$_2$ was increased to 0.8% [17].

There is a lack of studies that have investigated the influence of CaCl$_2$ in cement under exposure to HPHT conditions. Previous studies were conducted at ambient conditions, which is at atmospheric pressure and temperature and hence different to the downhole HPHT conditions [15–17]. Furthermore, previous studies predominantly focused on concrete, where the composition of concrete is different to well cement [17,18]. Even though several studies have been conducted to study the influence of CaCl$_2$ on GPC, HPHT conditions were not adopted in their experimental work [14].

The effect of the concentration of CaCl$_2$, as the accelerator, on the compressive strength and acoustic impedance of GPC for well cement, under exposure to HPHT conditions, is presented. In addition, the morphology and transit time of the samples were analyzed to support the compressive strength and acoustic impedance data.

2. Materials and Methods

Fly ash was selected as the aluminosilicate source for the preparation of GPC samples. It was obtained from the Tanjung Bin power plant, which is a 2100-MW coal-fired power plant located in Johor, Malaysia [19]. The fly ash was categorized as Class F fly ash, with a maximum calcium oxide (CaO) content of 6.72% according to the American Society for Testing Materials (ASTM) as per ASTM C618-19 [20]. The composition of the fly ash in comparison to the compliance requirements of ASTM C618-19 [20] for Class F fly ash is presented in Table 2. The spherical structure, as captured by a scanning electron microscope (SEM), is shown in Figure 2.
Sodium hydroxide (NaOH) and sodium silicate (Na$_2$SiO$_3$) were employed as the alkaline activator to activate the geopolymerization reaction of the aluminosilicate. The NaOH, with a concentration of 50% and a molarity of approximately 12.76 M, was obtained from Merck KGaA. Na$_2$SiO$_3$ was obtained from R&M Chemical with a solid content that ranged from 51% to 54%. The ratio of NaOH to Na$_2$SiO$_3$ was 1:1. CaCl$_2$ was obtained from Schlumberger Limited with a specific gravity of 1.32.

Table 2. Composition and properties of the fly ash obtained from the Tanjung Bin power plant in comparison to the compliance requirements of ASTM C618-19 [20] for Class F fly ash.

| Composition/Properties                        | Compliance Requirements as per ASTM C618-19 [20] for Class F Fly Ash | Fly Ash of the Tanjung Bin Power Plant |
|-----------------------------------------------|-----------------------------------------------------------------------|---------------------------------------|
| Silicon Dioxide (SiO$_2$)                     | ≥70                                                                   | 80.9                                  |
| + Aluminium Oxide (Al$_2$O$_3$)               |                                                                       |                                       |
| + Iron Oxide (Fe$_2$O$_3$) (% by weight)      |                                                                       |                                       |
| Calcium Oxide (CaO)                           | ≤20                                                                   | 6.72                                  |
| (% by weight)                                 |                                                                       |                                       |
| Moisture Content (% by weight)                | ≤3                                                                    | 0.08                                  |
| Loss of Ignition (% by weight)                | ≤6                                                                    | 0.43                                  |
| Specific Gravity                              | Nil                                                                   | 2.6521                                |

Figure 2. Spherical structure of the fly ash sample.

Five GPC samples, including the control sample, were prepared with concentrations of CaCl$_2$ that varied from 1% to 4%. The density of all samples was fixed at 15 ppg, and the weights of the constituents of each sample are presented in Table 3.
Mixing of the alkaline activator with GPC was performed using a Model 686CS constant speed mixer that was manufactured by Fann Instrument Company as shown in Figure 3, which complies with the recommended practice of the American Petroleum Institute (API), as per Section 5: Preparation of Slurry in API Recommended Practice 10B-2 [21]. All of the liquid materials were mixed at a rotational speed of 4000 rpm. Once the fly ash was completely poured into the mixer, the speed of the mixer was increased to 12,000 rpm for 35 s.

Table 3. Weights (g) of the constituents of each geopolymer cement (GPC) sample.

| GPC Sample | Class F Fly Ash | NaOH | Na₂SiO₃ | Water | CaCl₂ |
|------------|----------------|------|---------|-------|-------|
| Control    | 646.99         | 120  | 120     | 193.45| -     |
| GPC1       | 644.55         | 120  | 120     | 189.19| 6.69  |
| GPC2       | 642.24         | 120  | 120     | 185.16| 13.03 |
| GPC3       | 639.93         | 120  | 120     | 181.13| 19.37 |
| GPC4       | 637.62         | 120  | 120     | 177.10| 25.71 |

Once the mixing was completed, the slurry was poured into a 2 inch × 2 inch × 2 inch cement mold. Prior to pouring the cement, grease was applied to the interior surface of the mold to ease the process of re-molding. A stirrer was used to puddle the cement slurry during pouring to remove air bubbles, which can affect the mechanical behavior of the cement. Then, the cement was cured in the pressure temperature chamber to expose the cement to 3000 psi and 100 °C for 48 h to simulate HPHT conditions. After 48 h, the hardened cement sample, as shown in Figure 4, was re-molded using the cement mold. The cross-sectional surface area of the cement cube was measured using a caliper ruler to obtain an accurate measurement. The cross-sectional surface area of the hardened cement sample was approximately 4 inch².

The non-destructive test was performed by measuring the transit time across the cement cube. The calibration of the transducer was carried out by measuring the transit time across the steel bar prior to measuring the cement cube. To increase the accuracy, four readings, in μs/inch, were taken for each cement cube and the average was taken as the final value. The destructive test was then conducted by performing crushing tests on
the cement cubes using a calibrated API compressive strength tester of Model 4207D that was manufactured by Ametek Chandler Engineering, as shown in Figure 5. Intact cement cubes were placed at the center of the bearing load plate, as shown in Figure 6. The gauge displays the highest compressive load just before the cement breaks. The compressive load at the point of failure was then divided by the cross-sectional surface area of the sample to obtain the compressive strength, as shown in Equation (3). Destructive and non-destructive tests were repeated for each sample, and the average value for each cement design was calculated and recorded. Morphology tests were performed on the crushed cement samples as shown in Figure 7.

\[ F = \frac{P}{A} \]  

where the compressive strength (F), compressive load at the point of failure (P), and the cross-sectional surface area of the sample (A) are measured in psi, lbf, and inch\(^2\), respectively.

Figure 4. Hardened cement samples.

Figure 5. American Petroleum Institute (API) compressive strength tester.
Figure 6. Intact cement cube placed at the center of the bearing load plate.

Figure 7. Crushed cement sample.

Process flow of the overall methodology adopted to conduct the experimental work is depicted in Figure 8.
Figure 8. Process flow of the overall methodology.
3. Results and Discussion

3.1. Effect of Calcium Chloride (CaCl$_2$) on Compressive Strength ($F$) of GPC

The compressive strength ($F$) of the GPC samples, with varying concentrations of CaCl$_2$, after curing at 3000 psi and 100 °C for 48 h, is shown in Figure 9. All the samples that contain CaCl$_2$ have lower compressive strength than the control sample, which is 2917 psi. The decline in compressive strength relative to the control sample ranges from 12.8% to 50.7%. No significant trend can be observed in the compressive strength as the concentration of CaCl$_2$ increased from 1% to 4%. Among the samples that contain CaCl$_2$, the highest compressive strength of 2541 psi was obtained by GPC1, while the lowest compressive strength of 1437 psi was obtained by GPC4. Similar compressive strength values of 2542 psi, 2324 psi, and 2500 psi were obtained by GPC1, GPC2, and GPC3, respectively, with a trivial difference of 8.5% between the highest and lowest values obtained by GPC1 and GPC2. Conversely, GPC4 obtained the lowest compressive strength value with a 43% difference relative to GPC1. Instead of having higher compressive strength with the addition of CaCl$_2$ as in OPC, all GPC samples show opposite results, where the samples have lower compressive strength than the control samples. It can be concluded that GPC samples react differently to CaCl$_2$ compared with OPC with similar additives.

These findings were compared with those of two previous studies [16,18] in Figure 10. Both studies considered the compressive strength of cement samples at atmospheric pressure, whereas the present study focused on HPHT conditions. One study [18] focused on OPC as the well cement material, whereas the other study [16], along with the present study, focused on a geopolymer as the alternative to OPC. In the study that focused on OPC [18], it was revealed that the compressive strength of OPC samples that were cured at 27 °C for 24 h increased from 1829 psi to 2119 psi, 2409 psi, 2700 psi, and 2888 psi as the concentration of CaCl$_2$ increased from 2% to 4%, 6%, 8%, and 10%, respectively. Furthermore, the compressive strength of the OPC samples, when cured at 66 °C for 24 h, also indicated a similar trend, where it increased from 3182 psi to 3616 psi, 4048 psi, and 4483 psi as the concentration of CaCl$_2$ increased from 2% to 4%, 6%, and 8%, respectively. In
contrast, the compressive strength decreased from 4483 psi to 3842 psi as the concentration of CaCl$_2$ was increased further to 10%. In the other study that focused on GPC [16], a reduction in compressive strength was observed in the GPC sample that had been cured at 65 °C as the concentration of CaCl$_2$ increased from 1% to 2%, and it was also revealed that the GPC sample demonstrated the highest compressive strength at a CaCl$_2$ concentration of 1%. However, the compressive strength of both samples was higher than that of the control GPC sample, which was 3742 psi. No direct relationship was found between the concentration of CaCl$_2$ and compressive strength.

Figure 10. $F$ versus CaCl$_2$ concentration of GPC of the present study in comparison to the GPC in [16] and the OPC in [18].

The compressive strength distribution of the present study was supported by the microstructure observation from all samples. The scanning electron microscope (SEM) image showed that the control GPC sample was made up of intragranular structures and the presence of crosslinking was observed between each intragranular structure, as shown in Figure 11. It can be concluded that the intragranular structure and crosslinking contributed to the higher strength as demonstrated by the control sample.

When CaCl$_2$ was introduced into the GPC, the SEM image showed a significant presence of intergranular and spherical structures, as shown in Figure 12. At the same time, the presence of dendritic structures was observed on the spherical structure, while the crosslinking structure was not detected from the SEM image of GPC1.
Figure 11. (a) Intragranular structure of the GPC control sample; (b) Crosslinking between each intragranular structure.

Figure 12. Presence of dendritic structure on the spherical structure surface of the GPC1 sample.

The dendritic structure grew as the CaCl$_2$ concentration was increased from 1% to 2%, as shown in Figure 13. Similar to GPC1, GPC2 consisted of intragranular and spherical structures.

Figure 13. Growth of the dendritic structure on the surface of the spherical structure of the GPC2 sample.
The GPC3 sample exhibited a dense intragranular structure as shown in Figure 14. At the same time, unreacted fly ash was also observed. The dendritic structure of GPC3 was longer and more visible compared to that of GPC2.

![Figure 14. Presence of unreacted fly ash on the GPC3 sample.](image)

As the GPC1, GPC2, and GPC3 samples did not have significant differences in compressive strength values, which only varied by 8.5%, the SEM images also concluded that these samples have similar structures, which comprise intragranular and spherical structures, with the presence of dendritic structures. Meanwhile, SEM images of the GPC4 sample revealed the presence of cracking, as shown in Figure 15, as well as a needle-shaped structure, as shown in Figure 16, which corroborates the compressive strength value obtained by the GPC4 sample that was lower than all of the other samples.

![Figure 15. Cracking on the GPC4 sample.](image)
3.2. Effect of Calcium Chloride (CaCl$_2$) on the Acoustic Impedance (Z) of GPC

Figure 17 reveals that the transit time ($\Delta t$) increased with the increase in the concentration of CaCl$_2$ from 1% to 3%, but decreased as the concentration of CaCl$_2$ increased from 3% to 4%. Hence, the findings indicated that the transit time for GPC did not correlate with the compressive strength. The transit time, which has been converted from $\mu$s/inch to s/m, was then employed to simplify the calculation of acoustic impedance, which is presented in Table 4. Even though the transit time for the GPC samples was within the range of the conventional OPC, it should be noted that the range of transit time for the GPC sample was smaller, which was from 2.9103 s/m to 3.8017 s/m, compared to the conventional OPC [22], which was from 2.9528 s/m to 5.2493 s/m. Accordingly, as presented in Figure 18, the acoustic impedance values of the GPC samples ranged from 4.7278 Mrayl, as obtained by GPC3, to 6.1760 Mrayl, as obtained by GPC1. Hence, the range was smaller than that of the conventional OPC [22], which was from 3.4240 Mrayl to 6.0872 Mrayl. In order to increase the accuracy of the cement bond log tool, calibration of the cement bond log tool with new values of acoustic impedance prior to logging is recommended.

![Figure 16. Needle-shaped structure on the GPC4 sample.](image1)

![Figure 17. $F$ and transit time ($\Delta t$) of GPC sample at varying CaCl$_2$ concentrations.](image2)
Table 4. \( \Delta t \), acoustic velocity \((V)\), and acoustic impedance \((Z)\) of the conventional OPC (based on [22]) and GPC samples.

| Cement Sample         | \( \Delta t \) \((s/m \times 10^{-4})\) | \( V \) \((m/s \times 10^3)\) | \( Z \) \((\text{Mrayl})\) |
|-----------------------|------------------------------------------|-------------------------------|-------------------------|
| Conventional OPC (based on [22]) | 2.9528–5.2493                           | 1.9050–3.3867                 | 3.4240–6.0872           |
| GPC1                  | 2.9103                                   | 3.4361                        | 6.1760                  |
| GPC2                  | 3.4115                                   | 2.9313                        | 5.2686                  |
| GPC3                  | 3.8017                                   | 2.6304                        | 4.7278                  |
| GPC4                  | 3.6257                                   | 2.7581                        | 4.9573                  |

Figure 18. \( F \) and acoustic impedance \((Z)\) of GPC samples at varying CaCl\textsubscript{2} concentrations benchmarked against conventional OPC (based on [22]).

4. Conclusions

An investigation into the effect of the concentration of CaCl\textsubscript{2} used as an accelerator on the compressive strength and acoustic impedance of GPC for well cement, under exposure to HPHT conditions, has been conducted. Five samples with a density of 15 ppg were prepared with concentrations of CaCl\textsubscript{2} that varied from 1% to 4% by weight of cement. Findings indicate that the reaction of CaCl\textsubscript{2} as an accelerator in GPC demonstrated an impact that is different from that of an OPC sample. The GPC samples containing CaCl\textsubscript{2} have lower compressive strengths compared to those of the control sample. No significant trend can be observed as the concentration of CaCl\textsubscript{2} is increased. It can be concluded that the addition of 1% CaCl\textsubscript{2} by weight of cement is the optimum concentration for the curing conditions of 100 °C and 3000 psi for 48 h, which resulted in the highest compressive strength of the product. The compressive strength findings were supported by morphology studies. No correlation can be established between the transit time and compressive
strength data. The transit time data contributed to the acoustic impedance calculation, where it can be observed that the GPC samples containing CaCl$_2$ have a smaller range of acoustic impedance compared to those of OPC.

Several recommendations can be made for future research based on the present findings. A comparison study can be conducted to analyze the difference between OPC and GPC samples with the addition of CaCl$_2$ at curing conditions of 100 $^\circ$C and 3000 psi for 48 h. The chemistry between CaCl$_2$ and GPC needs to be further evaluated using chemical analysis, such as Raman spectroscopy and X-Ray diffraction techniques. Furthermore, even though 1% CaCl$_2$ provided the highest compressive strength for GPC, other well cement parameters, such as thickening time, rheology, shrinkage and fluid loss, should also be evaluated to identify the GPC design that can fit all of the parameters that are required by the well cement. Further studies can be performed to identify well cement additives other than CaCl$_2$ that can serve as the accelerator for GPC, which may result in higher compressive strength than the control sample. The range of acoustic impedance in the present study is dedicated to GPC with CaCl$_2$, and thus more experimental work should be conducted to find the transit time data for GPC that are incorporated with other additives in order to determine the acoustic impedance for GPC for well cement. The relationship between transit time and the morphology of GPC can be further analyzed to better understand the wave propagation through different types of internal cement structure and the influence of the transit time on the structure.

Author Contributions: Conceptualization, N.N.Z., Y.A.S., N.S., and S.H.A.R.; methodology, N.N.Z. and S.H.A.R.; formal analysis, N.N.Z. and A.I.A.H.; resources, S.H.A.R. and M.F.H.; data curation, N.N.Z., A.I.A.H., and M.F.H.; writing—original draft preparation, N.N.Z. and S.A.F.; writing—review and editing, N.S. and S.A.F.; visualization, N.N.Z. and S.A.F.; supervision, N.S. and S.H.A.R.; project administration, S.A.F., Y.A.S., and N.S.; funding acquisition, N.N.Z. and Y.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by PETRONAS Research Sdn. Bhd., Malaysia, via project cost centre 015MD0-064, as administered by the Research Management Centre of Universiti Teknologi PETRONAS, Malaysia, and the project cost centre E.025.GST.02019.003, as per the record of PETRONAS Research Sdn. Bhd.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from PETRONAS Research Sdn. Bhd. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the corresponding author, N.N.Z., with the permission of PETRONAS Research Sdn. Bhd.

Acknowledgments: The authors are thankful to the technologists of Universiti Teknologi PETRONAS and PETRONAS Research Sdn. Bhd., especially to Ahmad Faris bin Ahmad Othman, Ts. ChM. Nadzhratul Husna binti Ahmad Puad, and Mohamad Asmai bin Mohamad Arof, for the commitment and support to carry out various activities related to the experimental work in the laboratory inclusive of the preliminary testing.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| API          | American Petroleum Institute |
| ASTM         | American Society for Testing Materials |
| atm P        | Atmospheric Pressure |
| bwoc         | by weight of cement |
| C-S-H        | Calcium-Silicate-Hydrate |
GPC  Geopolymer Cement
HPHT  High Pressure and High Temperature
OPC   Ordinary Portland Cement
SEM   Scanning Electron Microscope
WOC   Waiting-on-Cement

Chemical Formulae

\[ \text{Al}_2\text{O}_3 \] \quad \text{Aluminium Oxide}
\[ \text{CaCO}_3 \] \quad \text{Calcium Carbonate}
\[ \text{CaCl}_2 \] \quad \text{Calcium Chloride}
\[ \text{CO}_2 \] \quad \text{Carbon Dioxide}
\[ \text{CaO} \] \quad \text{Calcium Oxide}
\[ \text{H}_2\text{CO}_3 \] \quad \text{Carbonic Acid}
\[ \text{H}_2\text{S} \] \quad \text{Hydrogen Sulfide}
\[ \text{Fe}_2\text{O}_3 \] \quad \text{Iron Oxide}
\[ \text{SiO}_2 \] \quad \text{Silicon Dioxide}
\[ \text{NaOH} \] \quad \text{Sodium Hydroxide}
\[ \text{Na}_2\text{SiO}_3 \] \quad \text{Sodium Silicate}

Notations

\[ Z \] \quad \text{Acoustic Impedance}
\[ V \] \quad \text{Acoustic Velocity}
\[ P \] \quad \text{Compressive Load at the Point of Failure}
\[ F \] \quad \text{Compressive Strength}
\[ A \] \quad \text{Cross-Sectional Surface Area}
\[ \rho \] \quad \text{Density}
\[ \Delta t \] \quad \text{Transit Time}

References

1. Bligh, R.; Glasby, T. Development of Geopolymer Precast Floor Panels for the Global Change Institute at University of Queensland. In Proceedings of the 26th Biennial National Conference of the Concrete Institute of Australia (Concrete 2013), Gold Coast, Australia, 16–18 October 2013; Dao, V., Dux, P., Eds.; Concrete Institute of Australia: Sydney, Australia, 2013.
2. Glasby, T.; Day, J.; Genrich, R.; Aldred, J. EFC Geopolymer Concrete Aircraft Pavements at Brisbane West Wellcamp Airport. In Proceedings of the 27th Biennial National Conference of the Concrete Institute of Australia (Concrete 2015), Melbourne, Australia, 30 August–2 September 2015; International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM), Concrete Institute of Australia: Sydney, Australia, 2015.
3. Davidovits, J.; Cordi, S.A. Synthesis of New High Temperature Geo-Polymers for Reinforced Plastics/Composites. In Proceedings of the SPE PACTEC ‘79, Costa Mesa, CA, USA, 31 January–2 February 1979; Society of Plastics Engineers: Brookfield Center, OH, USA, 1979; pp. 151–154.
4. Shill, S.K.; Al-Deen, S.; Ashraf, M.; Hutchison, W. Resistance of fly ash based geopolymer mortar to both chemicals and high thermal cycles simultaneously. Constr. Build. Mater. 2020, 239, 117886. [CrossRef]
5. Rahman, S.H.A.; Zulkarnain, N.N.; Shafiq, N. Experimental study and design of experiment using statistical analysis for the development of geopolymer matrix for oil-well cementing for enhancing the integrity. Crystals 2021, 11, 139. [CrossRef]
6. Nasvi, M.M.C.; Gamage, R.P.; Jay, S. Geopolymer as well cement and the variation of its mechanical behavior with curing temperature. Greenh. Gas Sci. Technol. 2012, 2, 46–58. [CrossRef]
7. Duguid, A.; Radonjic, M.; Bruant, R.; Mandecki, T.; Scherer, G.; Celia, M. The Effect of Carbon Dioxide Sequestration on Oil Well Cements; Department of Civil Engineering, Princeton University: Princeton, NJ, USA, 2009.
8. Barlet-Gouédard, V. Well technologies for CO₂ geological storage: CO₂-resistant cement. Oil Gas Sci. Technol. 2007, 62, 325–334. [CrossRef]
9. Uehara, M. New concrete with low environmental load using the geopolymer method. QR RTRI 2010, 51, 1–7. [CrossRef]
10. Hewayde, E.; Nehdi, M.; Allouche, E.; Nakha, G. Effect of geopolymer cement on microstructure, compressive strength and sulphuric acid resistance of concrete. Mag. Concr. Res. 2006, 58, 321–331. [CrossRef]
11. Lloyd, N.; Rangan, B. Geopolymer Concrete with Fly Ash. In Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, Università Politecnica delle Marche, Ancona, Italy, 28–30 June 2010.
12. Kapp, P. Effect of calcium chloride on Portland cements and concretes. Nat. Bur. Stand. 1935, 14, 499–517. [CrossRef]
13. Samson, O.T.M.D.; Omoniyi, T.M. Correlation between non-destructive Testing (NDT) and destructive testing (DT) of compressive strength of concrete. Int. J. Eng. Sci. Invent. 2014, 3, 12–17.
14. Salain, I.M.A.K. Using calcium chloride as an accelerator for Portland pozzolan cement concrete compressive strength development. IOP Conf. Ser. Mater. Sci. Eng. 2019, 615, 012016. [CrossRef]
15. Vehmas, T.; Kronlöf, A.; Cwirzen, A. Calcium chloride acceleration in ordinary Portland cement. Mag. Concr. Res. 2017, 70, 856–863. [CrossRef]
16. Rattanasak, U.; Pankhet, K.; Chindaprasirt, P. Effect of chemical admixtures on properties of high-calcium fly ash geopolymer. *Int. J. Miner. Metall. Mater.* **2011**, *18*, 364–369. [CrossRef]

17. Safvana, T.S.; Shehin, A.S.; Salim, S.; Kuruvilla, G. Experimental investigation on the performance of calcium chloride and geogrid in concrete. *Int. Res. J. Eng. Technol.* **2019**, *6*, 5160–5163.

18. Rosyidan, C. The effect of using calcium chloride in G Class cement on starting time and cement pressure. *PETRO J. Ilm. Tek. Perminyakan* **2019**, *8*, 91–94. [CrossRef]

19. Our Business: Power Plant and Water Desalination Plant Locations. Available online: [https://www.malakoff.com.my/Our-Business/Power-Plant-and-Water-Desalination-Plant-Locations/](https://www.malakoff.com.my/Our-Business/Power-Plant-and-Water-Desalination-Plant-Locations/) (accessed on 27 April 2021).

20. ASTM C618–19: *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, ASTM International: West Conshohocken, PA, USA, 2019. [CrossRef]

21. *API RP 10B-2: Recommended Practice for Testing Well Cements*, 2nd ed.; American Petroleum Institute (API): Washington, DC, USA, 2019.

22. Smolen, J.J. *Cased Hole and Production Log Evaluation*; PennWell Publishing Company: Tulsa, OK, USA, 1996.