Properties of Neat and Blended Concrete Systems Exposed to Standard 20°C and Elevated 38°C Temperature Conditions

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Abstract. The quality of in-situ concrete is partly dependent upon the temperature and exposure conditions where the concrete is placed. Incorporation of cement replacements such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS) may be beneficial from economic and environmental sustainability perspectives, due to industry by-products utilisation. Their potential benefits towards concrete properties are becoming expected, such that countries like Brunei Darussalam, which do not locally produce these by-products, are now importing and incorporating them. A study is done investigating neat and blended concrete systems exposed to 20°C standard and 38°C elevated temperatures. Properties compared include consistencies (workabilities), compressive strengths and heat evolutions. The same concreting materials were used throughout to reduce discrepancies from different batches. Backscattered electron (BSE) micrographs of the concrete systems supported findings. For the range of systems studied, the findings include elevated temperature mixes having lower consistencies and late-age strengths, and higher early-age strengths and heat evolutions compared to standard temperature mixes, irrespective of cement replacement. Blended concrete mixes had higher consistencies, lower heat evolutions and lower early age strengths, and in general did not exceed the late age strengths when compared to the corresponding neat concrete mixes.

1. Introduction
The quality of in-situ concrete is dependent upon the weather and exposure conditions where the concrete is placed. The concrete properties are likely to be affected by these conditions, in addition to quality of workmanship. Incorporation of cement replacements such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS) has potential benefits from economic and environmental sustainability perspectives, due to utilisation of industry by-products. There are also potential benefits with respect to the concrete properties such as potential improved hardened properties [1] [2]. Countries such as Brunei Darussalam do not utilise coal for power generation nor have raw iron industries, and subsequently PFA and GGBS are not available locally. In spite of this, the potential benefits are becoming more appreciated such that locally-based concrete producers have started to import and incorporate these by-products specifically for the benefits. The geographic location of Brunei means that it experiences hot weather conditions and therefore additional precautions must be undertaken to ensure the concrete remains durable in its intended service environment. The hot weather conditions mean the likelihood of increased cement reaction rate. Similarly, corrosion of the reinforcement for reinforced concrete is more likely as compared to areas which are not exposed to these temperatures. This is partly because corrosion, as with many chemical reactions, occurs faster at increased temperatures [1].

The benefits of appreciating the microstructural properties of concrete and relating it with the macrostructural properties are becoming more appreciated, especially with modern technologies. The
Scanning Electron Microscope (SEM) is becoming a key technique for microstructural study of concrete. This article reports results of tests comparing the engineering properties of neat and blended concrete systems exposed to standard and elevated temperature conditions, and supported by qualitative microstructural observations of those systems. The tests comprise part of a research study of the microstructure and engineering properties of neat and blended reinforced concrete systems exposed to different temperature conditions. The tests and results reported here aim to provide justification and support the concrete systems used in the main study.

2. Experimental Methodology

2.1. Materials
The main binder used was ordinary Portland Cement, which also conforms to BS EN 197 Portland Cement CEM 1 classification, having mineral composition approximately 50.4% C₃S, 22.2% C₅S, 8.4% C₃A and 9.2% C₄AF, henceforth referred as OPC. Ground Granulated Blast Furnace Slag (GGBS), and Pulverised Fuel Ash (PFA) of Class F, were used as partial cement replacement. The chemical properties of the binders are summarised in Table 1. The fine aggregates (FA) and coarse aggregates (CA) (10mm nominal maximum size) were both gravel type. Clean and potable water was used throughout. The same materials from a specific batch were used throughout to reduce possible discrepancies from using different batches.

Table 1. Chemical Data for OPC, PFA and GGBS Used in Study.

| Chemical Constituent | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | Na₂O | K₂O | TiO₂ | SO₃ |
|----------------------|------|-------|-------|-----|-----|------|-----|------|-----|
| OPC                  | 21.15| 5.13  | 3.04  | 64.51| 2.15| 0.27 | 0.58| -    | 2.67|
| PFA                  | 51.9 | 26.9  | 11.3  | 1.5 | 1.6 | 1.2  | 3.8 | 0.9  | 0.6 |
| GGBS                 | 34.45| 13.21 | 0.60  | 38.07| 8.06| <0.30| 0.41| 0.49 | -   |

2.2. Exposure Conditions & Concreting
Relevant engineering and/or microstructural studies concerning effects of different temperature conditions showed various temperatures being used (e.g. [2]-[5]); however many were compared against 20°C temperature, thus is termed standard temperature. This was compared against 38°C temperature, corresponding to a large temperature difference but still a realistic ambient temperature, and termed elevated temperature. Relative Humidity used was 100% RH at both temperatures to reduce discrepancies and also that many studies (e.g. [2]-[5]) use this RH condition. The standard 20°C & 100%RH was achieved using a fog curing room, set at 20°C ±2°C & 100%RH. The elevated 38°C & 100%RH was achieved using an environment chamber, set at 38°C ±2°C, with specimens enclosed in sealed bags containing an exposed container of water. The chamber humidity was adjustable, but was less feasible to be set to 100%RH due to safety aspects. The experimental programme was done in temperate climate, hence it was important to ensure the simulated elevated temperature be as realistic as possible with on-site conditions. For the elevated temperature mixes, the concreting materials were stored in the environment chamber until immediately prior to concreting to ensure their temperature was at the chamber’s set temperature. Concreting was done in as minimal time as possible, and after placing in the specimen moulds and compacted, were transferred immediately to the required exposure environment. This process ensured minimal loss of temperature.

2.3. Neat and Blended Concrete Systems Used
A 0.50 water-binder (w/b) ratio and 3:2:1 mix proportion of CA:FA:binder was used throughout. This w/b and mix proportion was found optimal for the exposure conditions, materials and tests utilised based on preliminary and trial mixes results. Full compaction was achieved for all mixes discussed without the need for chemical admixtures. Neat concrete (i.e. OPC as binder) and blended concrete systems (i.e. OPC + cement replacement as binders) were used. Cement replacement proportions used were 40% PFA, 50% GGBS and 70% GGBS by percentage weight. Mixes are given mix designations
OPC20C, OPC38C, 40PFA20C, 40PFA38C, 50GGBS20C, 50GGBS38C, 70GGBS20C and 70GGBS38C Mixes, labelled in accordance to proportions, inclusions and temperature conditions. A neat concrete mix exposed to elevated temperature and using water at 5°C lowered temperature immediately prior to concrete mixing was also produced, and designated as Cold-OPC38C Mix. This article discusses the results and findings from these 9 mixes.

2.4. Tests
The mean slump was the average of 2 Slump Tests measured to the nearest 5mm for a specific mix, using methodology specified in BS EN 12350-2:2000. The mean compressive strength at a specific age was the average compressive strengths at failure of 3 cube specimens of 100mm dimensions of compressive strengths at failure, using methodology as recommended in BS EN 12390-3:2002. Concrete temperature was measured using copper-constantan T-Type thermocouples connected to a data-logger and recorded temperature at specific intervals. Temperature evolution was measured for concrete in a purpose-built cube timber mould of internal dimensions 150mm, and covered with wet hessian and plastic cover. Other tests were also done for the systems and included conduction calorimetry and thermogravimetric analysis of the corresponding cement specimens, and the major scope of work, a study of the microstructure and interfaces of reinforced concrete systems exposed to the mentioned exposure conditions and will be published elsewhere.

3. Results and Findings
3.1. Concrete Consistence Results
The Mean Slump Test results are shown in Figure 1 and summarised in Table 2. The findings are as follows:

1. All elevated temperature mixes had lower consistencies than their corresponding mix at standard temperature. The OPC mixes showed the greatest difference, being almost twice in magnitude at standard temperature. The 40PFA mixes showed the least differences between the 2 temperatures.
2. Incorporation of PFA or GGBS resulted in an increase in consistence regardless of temperature. However, there was no general similar trend for the consistencies of the mixes at a similar exposure condition. At standard temperature, the 70GGBS20C Mix had the highest slump; at elevated temperature it was the 40PFA38C Mix.
3. Incorporation of PFA or GGBS had a more pronounced effect in increasing consistence at elevated temperature compared to standard temperature. A comparison between PFA and GGBS showed that PFA incorporation increased the consistence more, even though percentage replacement was lower.
4. A comparison between the OPC38C Mix and the Cold-OPC38C Mix showed a significant increase in consistence in spite of only water temperature being reduced.

![Figure 1. Mean Slump Test Results](image1)

![Figure 2. Temperature Evolution of Concrete In First 24 Hours](image2)
Table 2. All Concrete Mixes - Mean Slumps and Mean Compressive Strengths At Specified Ages for all Concrete Mix Systems.

| Mix                | Mean Slump (mm) | Mean Compressive Strength (MPa) at Age |
|--------------------|-----------------|---------------------------------------|
|                    |                 | 1 Day    | 3 Day  | 7 Day  | 28 Day | 270 Day |
| OPC20C Mix         | 87.5            | 14.60    | 30.35  | 43.70  | 59.70  | 76.80   |
| OPC38C Mix         | 42.5            | 26.50    | 39.00  | 46.90  | 53.30  | 64.28   |
| 50GGBS20C Mix      | 105             | 8.05     | 19.65  | 30.15  | 50.65  | 80.20   |
| 50GGBS38C Mix      | 62.5            | 18.15    | 32.20  | 45.50  | 54.45  | 60.64   |
| 70GGBS20C Mix      | 115             | 4.35     | 11.40  | 22.31  | 43.00  | 66.60   |
| 70GGBS38C Mix      | 75              | 12.40    | 27.70  | 38.71  | 47.10  | 51.37   |
| 40PFA20C Mix       | 102.5           | 6.16     | 14.21  | 21.58  | 32.30  | 61.33   |
| 40PFA38C Mix       | 87.5            | 13.65    | 22.81  | 33.85  | 48.45  | 53.06   |
| Cold OPC38C Mix    | 85              | 29.22    | 41.05  | 49.55  | 55.25  | 68.19   |

3.2. Temperature Evolution Results

The temperature evolution graph during the first 24 hours after concrete mixing stage is shown in Figure 2. The approximate initial and peak temperatures, and time at peak temperature is summarised in Table 3. Temperature measurement could only be started a half hour after the start of concrete mixing due to practicality reasons. Nevertheless, this was consistent throughout, and can be representative for Initial Temperature. The 50GGBS20C and 70GGBS20C Mixes results are excluded since the cover could only be applied a few hours later, and hence compromised the graphs. The findings are as follows:

1. All elevated temperature mixes resulted in higher peak temperatures and earlier time of peak temperatures when compared to their corresponding mix at standard temperature.
2. Irrespective of temperature condition, incorporation of PFA or GGBS resulted in lower initial concrete temperature, lower peak temperature and a later time of peak temperature. Furthermore, the relationship between the OPC and PFA mixes were similar at both exposure conditions.
3. The Cold-OPC38C Mix showed lower initial concrete temperature, lower peak temperature, and slightly later time of peak temperature compared to the OPC38C Mix.

Table 3. Approximate Concrete Initial and Peak Temperatures, and Time at Peak Temperatures.

| Mix                | Initial Temperature (°C) | Peak Temperature (°C) | Time at Peak Temperature (hours) |
|--------------------|--------------------------|-----------------------|----------------------------------|
| OPC20C Mix         | 17                       | 29                    | 10.5                             |
| 40PFA20C Mix       | 16                       | 24                    | 12.5                             |
| OPC38C Mix         | 33                       | 50                    | 7                                |
| 40PFA38C Mix       | 30.5                     | 45                    | 10                               |
| 50GGBS38C Mix      | 32                       | 43                    | 10.5                             |
| Cold-OPC38C Mix    | 26.5                     | 45                    | 8                                |

It should also be appreciated that temperature magnitudes are affected by the size and section measured [6]. Furthermore, there was still heat dissipation, albeit minimal, from the setup used. Separate tests were done with cement samples of similar mix proportions, replacement levels and temperatures using Conduction Calorimetry. The findings are discussed separately; however it was found that the temperature profiles were comparable, whilst not similar in magnitudes. In this respect, since procedure and volume was consistent, relative comparisons between the mixes are justified.
3.3. Compressive Strength Results
The mean Compressive Strengths are summarised in Table 2 and shown in Figure 3 to Figure 7. These include comparisons of the standard temperature mixes; the elevated temperature mixes; the OPC mixes; the OPC & PFA mixes; and the OPC & GGBS mixes respectively. Mean strengths are taken at 1, 3, 7, 28 and 270 days, the latter considered as late age. The findings are as follows:

1. Irrespective of temperature, all OPC mixes showed the expected faster strength development at early ages up to 7 days, then slower rate up to 28 days, and even slower up to 270 days.
2. The elevated temperature mixes were of higher strengths at early ages compared to the corresponding standard temperature mixes. However, as age progressed, the strength development rates were comparatively slower. At 270 day age, all elevated temperature mixes were of lower strengths compared to their corresponding mixes.
3. Incorporation of GGBS resulted in lower strengths compared to the OPC mix irrespective of temperature. With progressing age, the percentage differences at corresponding ages became smaller. The percentage differences were also lower for the elevated temperature mixes compared to the standard temperature mixes. Only the 50GGBS20C Mix strength exceeded the OPC mix strength at late age.
4. Incorporation of PFA resulted in lower strengths compared to the corresponding OPC mixes irrespective of temperature. The differences remained large up to 270 days with differences of 15MPa (or 20%) for the 40PFA20C Mix and 11MPa (or 17%) for the 40PFA38C Mix.
5. The Cold-OPC38C Mix was marginally higher in strength than the OPC38C Mix at all ages. At 1 day age the difference was 2.5MPa (or 10%); by 270 day age, the difference was 4MPa (or 6%).

**Figure 3.** Mean Compressive Strengths of OPC Mixes.  
**Figure 4.** Mean Compressive Strengths Mixes Exposed to Standard Temperature.  
**Figure 5.** Mean Compressive Strengths Mixes Exposed to Elevated Temperature.
4. Analysis & Discussion of Results

4.1. Neat Concrete Systems Exposed to Different Temperature Conditions
The lower slump at elevated temperature compared to standard temperature is most likely due to the increased reaction of the binder(s). The binder paste would have a greater tendency to stiffen more quickly due to increased cement hydration reaction, specifically the aluminates, hence the reduced consistence. This proposal correlates well with the heat evolution and strength results at early ages. The concrete mixes initial temperatures of 17°C and 33°C exposed to 20°C standard and 38°C elevated temperatures respectively reinforce increased reaction is occurring with the elevated temperature mixes, specifically the aluminates which have the highest heat evolution. At 1 day age, the OPC38C Mix strength is 12MPa (or 81%) greater than the OPC20C Mix. This is confirmed (via microstructural analysis) to be greater C-S-H produced from the increased reaction of silicates at elevated temperature; results are published separately. The higher peak temperature of 50°C occurring at 7 hours for the OPC38C Mix as compared to 29°C at 10.5 hours for the OPC20C Mix reinforces the aluminates and silicates undergoing increased rate of reactions in the OPC38C Mix. However, with increasing age, the percentage difference in strengths reduced, and by 28 days, the OPC20C Mix had higher strength than the OPC38C Mix by 6MPa (or 10%); and at 270 day late age by 13MPa (or 12%). These results show that the OPC38C Mix high early strength at early ages has consequences whereby has likely resulted in less uniform distribution of cement hydration products.

4.2. Lower Temperature Concrete Materials at Elevated Temperature Conditions
The benefits of lower temperature materials in elevated temperatures is shown via comparison of the Cold-OPC38C and OPC38C Mix results, albeit the differences were not significantly large for strengths. Slumps increased from 42.5mm to 87.5mm. In on-site practice, this higher consistence will be beneficial for concreting purposes, more-especially at elevated temperatures. The concrete initial and peak temperatures have reduced by 6.5°C and 5°C respectively, with peak temperature occurring 1 hour later than the OPC38C Mix. This will be advantageous for the hardened stage, including more uniform strength development, and likely reduce thermal cracking. The latter possibility is not investigated in this study. The strengths improved from 3MPa (or 10%) to 4MPa (or 6%) increases at 1 day and 270 day ages respectively for the Cold-OPC38C Mix. It was expected that very early age strength would be lower, but was not the case. This may possibly be either a real occurrence or an experimental anomaly due to concrete variability. It is reiterated that only the water temperature was lowered; other concrete components remained at 38°C. Subsequently, even this practice will have beneficial effects on concrete exposed to elevated temperatures.
4.3. Blended Concrete Systems Exposed to Different Temperature Conditions

The lower slumps, higher initial and peak temperatures, earlier peak temperature times, and higher early age strengths for the blended concrete mixes at elevated temperature compared to standard temperature can be attributed to the increased reaction due to the higher temperature as discussed previously. Higher slumps with PFA and lower heats of hydration with PFA or GGBS were also reported by Khan et al [7] and Alshamshi [3] respectively. The higher slumps with incorporation of PFA or GGBS regardless of exposure condition may be partly due to the reduced OPC volume, thus resulting in lower initial reaction. This would also explain the finding that incorporation of PFA or GGBS has a more pronounced effect at elevated temperature, due to reduced OPC which would otherwise incur greater exothermic reaction. This may also be partly due to the physical properties of the cement replacements used. This is especially evident with the PFA mixes, whereby in spite of only 40% replacement had higher consistencies, even at elevated temperature. The spherical nature of the PFA particles would lead to the ball-bearing effect thus increasing consistence. The known glassy nature of GGBS particles would also lead to the increase in consistence; however their angular shape means this is less efficient than PFA. Figure 8 and Figure 9 show backscattered electron (BSE) micrographs (recorded using an SEM) of the PFA and GGBS incorporated reinforced concrete mixes respectively, showing the physical nature of the PFA and GGBS particles as discussed.

The significantly higher slump difference between the 40PFA38C Mix and the OPC38C Mix compared to other mixes at the 2 temperatures may be possibly due to the PFA ball-bearing effect having greater effect than the OPC increased reaction at elevated temperature. The lower PFA percentage replacement compared to GGBS should also be considered and reinforces the findings more. In terms of strengths, the optimum cement replacement level is GGBS at 50% at both temperatures, with differences with the corresponding OPC Mix being the lowest. At 270 days the 50GGBS20C Mix has exceeded the OPC20C Mix by 3MPa (or 4%), whilst the 50GGBS38C Mix is only lower than the OPC38C Mix by 4MPa (or 6%).

Figure 8- BSE Micrograph of 40PFA20C Mix at 500x Magnification.

Figure 9- BSE Micrograph of 50GGBS20C Mix at 500x Magnification.
4.4. Idealised OPC Strength Comparisons

Figure 10 to Figure 12 show compressive strength comparisons of the blended mixes with the idealised OPC compressive strength component of the mix; this is calculated from the percentage compressive strength of the corresponding OPC mix results.

Comparisons of the GGBS incorporated mixes with their OPC contributions at elevated temperature suggest that the GGBS contributed a significant part in the strength development starting from approximately 3 day age and is likely due to its latent hydraulic property. At standard temperature, there was minimal contribution from the GGBS reaction at 1 day age and as is expected, whilst at elevated temperature the contribution was more. At progressing ages, the on-going hydration and thus strength development of the GGBS appeared to contribute more to the strength. This was similar at both replacement levels and temperatures. GGBS appears beneficial at both temperature conditions.

Comparisons of the PFA incorporated mixes with their OPC contributions suggest that pozzolanic reaction of the PFA had less effect on the strengths at early ages and is only at later ages that the PFA contribute to the strengths; this is more-so for the 40PFA20C Mix. The strength of the 40PFA20C Mix is in fact lower than the equivalent OPC component until after 28 days suggesting the inclusion of PFA at earlier ages had a retarding effect on the OPC hydration. This may also be possibly be due to the percentage replacement level used in the study. The comparisons also suggest that the benefits of PFA incorporation is more utilised at elevated temperature.

Comparisons of the blended mixes with their OPC strength component also suggest that at a more optimum replacement level, incorporation of PFA or GGBS may result in further improved strength and exceed the neat concrete system, thus justifying the benefits of lower heat evolution and improved consistence with incorporation of cement replacement. This had been further reinforced with results from the different GGBS proportions used. Additionally, better curing may have improved the blended concrete properties, especially for the elevated temperature mixes [2]. At the same time, the findings confirm differences in properties of concrete systems between standard and elevated temperature conditions; and additionally utilisation of blended concrete in the temperatures used would result in differing effects. The systems used justify the mix selection of the main study, and the results presented in this article thus support the overall findings.

5. Conclusions
This article presented the findings of the engineering properties of neat and blended concrete systems exposed to standard and elevated temperatures. The results comprise part of a research to study the properties and microstructure of reinforced concrete systems and interfaces exposed to different temperatures. For the systems used, the following conclusions are summarised:
• Neat and blended concrete systems exposed to elevated temperature resulted in lower consistence, higher initial and peak concrete temperatures, earlier times of peak temperatures, higher early age strengths, and lower late age strengths compared to corresponding systems exposed to standard temperature.

• The blended concrete systems used resulted in higher consistence, higher initial and peak concrete temperatures, earlier times of peak temperatures and lower strengths, compared to the corresponding neat concrete systems. The only exception was the mix using GGBS at 50% replacement at standard temperature which had higher late age strength.

• Improvements to the hardened concrete properties are expected at more optimal replacement levels of GGBS, at both standard and elevated temperatures. This is similar with PFA, though results suggest that the PFA properties is more utilised at elevated temperatures.

• Reduction of water temperature for the neat concrete system exposed to elevated temperature resulted in higher consistence, lower initial and peak concrete temperature, later time of peak temperature, and higher strengths.

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