Properties of PFA Concrete at Different Curing Conditions

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Abstract. This paper investigates the effect of various curing conditions on the strength development and durability characteristics of PFA concrete. The concrete samples are placed in 3 different curing conditions: (i) saturated wet curing, (ii) air dried at room temperature, and (iii) sea water curing. The systems comprise of concrete mixes at decreasing water-cement ratio from 0.60 to 0.50 to 0.40 and constant PFA replacement at 30%. Neat concrete (100% OPC) and concrete incorporating both PFA and silica fume (SF) (10% SF, 20% PFA), further supports the study. Compressive strength was determined at concrete ages of 3, 7, 28 and 56 days. Water absorption test is done for samples at age of 28 and 56 days to measure the durability properties at the later ages. The study concluded that both seawater cured OPC and PFA concrete samples result in high early age strength up to 7 days. At later ages, there was no significant deterioration in strength for seawater cured concrete. Low water binder (w/b) ratio and silica fume enhance the performance of PFA concrete at all ages for all curing conditions.

1. Introduction

Seawater is normally avoided for curing due to the common perception of seawater as an aggressive medium to concrete especially reinforced concrete. With the ever-increasing demand of freshwater and limited resources, seawater may perhaps be a sustainable alternative option. This study explores the possibility of using seawater as curing water especially for marine constructions. However, marine concrete infrastructures are commonly expected to stand for a long service life and thus, durability is one of the main issues. Seawater constitutes mainly of chloride, sodium, magnesium, calcium and potassium ions. The most common deterioration due to seawater is crystallization as a result of sulphates present in seawater. [2] Sulphate attacks occur when these ions react with calcium hydroxide to form excessive gypsum which later reacts with calcium aluminate hydrate to form ettringite.[7]

Many studies have indicate that curing in seawater increases the compressive strength of OPC concrete only up to early ages of 7 to 14 days when compared to concrete cured normally in plain water.[1][3][4][5] At later ages, concrete casted and cured in freshwater increases gradually beyond the concrete cured in seawater.[3] The reduced compressive strength in concrete cured in seawater at later ages are suspected to result from the formation of delayed ettringite at the later ages.[1] This causes internal stresses within concrete and results in expansion and micro-cracking within the concrete which makes it weaker and more permeable. Furthermore, the higher early age strength in seawater cured concrete was suspected due to high temperature of seawater and the presence of sodium chloride.[1]

To give a better understanding of the effects of seawater, the performance of concrete cured in seawater, in this study, is compared against two curing extremes. This includes curing in plain water (i.e. saturated wet curing) and air drying at room temperature.
Lowering water-cement ratio allows for compensation of the reduction in strength and durability. Various studies concluded that low water-cement ratio reduces the permeability of the concrete and thus, its susceptibility to harmful agents in seawater. Moreover, the strength and durability of concrete may be potentially improved with the use of cement replacements such as pulverized fuel ash or silica fume.

The aim of this research is to study the effects of three curing conditions, which includes saturated wet curing, seawater curing and air drying, on the strength performance and durability characteristic of concrete with PFA and/or silica fume as cement replacements as well as PFA concrete with decreasing water-binder ratio. The objectives are, as follows:

1. To design OPC concrete and concrete with 30% cement replacement by PFA and/or silica fume and PFA concrete with decreasing water-binder ratio.
2. To conduct three curing conditions for each group of samples for a period of 3, 7, 28 and 56 days.
3. To determine the compressive strength of concrete samples at age of 3, 7, 28 and 56 days.
4. To determine the water absorption of concrete at the age of 28 and 56 days as an indication of its durability characteristics at later ages.

2. Methodology

2.1 Design Mix

To meet the stated aims, the following mix proportions (in kg/m³) are designed, which are summarized in Table 1. The OPC Mix was designed with a target slump of 30-60 mm. Concrete cubes of 100 x 100 x100 mm size were used for compressive strength and water absorption. Three concrete cubes are used to obtain the averaged results of both tests for each sample.

| Mix   | Cement (kg/m³) | Fly Ash (kg/m³) | Silica Fume (kg/m³) | Water (kg/m³) | Fine Aggregate (kg/m³) | Coarse Aggregate (kg/m³) |
|-------|----------------|-----------------|---------------------|---------------|------------------------|------------------------|
| Mix 1 | – 100% OPC, 0.60 w/c | 383             | 0                   | 0             | 230                    | 562.2                  | 1194.8                 |
| Mix 2 | – 70% OPC, 30% PFA, 0.60 w/b | 268.1           | 114.9               | 0             | 230                    | 562.2                  | 1194.8                 |
| Mix 3 | – 70% OPC, 30% PFA, 0.50 w/b | 322.0           | 138.0               | 0             | 230                    | 529.2                  | 1150.8                 |
| Mix 4 | – 70% OPC, 30% PFA, 0.40 w/b | 402.5           | 172.5               | 0             | 230                    | 469.5                  | 1095.5                 |
| Mix 5 | – 70% OPC, 20% PFA, 10% SF, 0.60 w/b | 268.1           | 76.6                | 38.3          | 230                    | 562.2                  | 1194.8                 |

2.2 Curing Conditions

After leaving the fresh concrete samples to harden under a wet burlap, the samples are then demoulded and subjected to the following three curing conditions:

1. **Saturated wet curing**: The demoulded concrete cubes are placed in a temperature-controlled curing tank of plain water until the day of test. The temperature is maintained at a range of 27°C to 30°C.
2. **Air dried**: The demoulded concrete cubes are placed in room temperature and humidity without any provision of water until the day of test.
3. **Exposure to sea water**: The demoulded concrete cubes are placed in a curing tank of artificial seawater until the required day of test. The temperature is maintained at a range of 27°C to
30°C. The artificial sea water is made using Instant Ocean sea salt which is added to dechorionized tap water in order to maintain consistency of seawater used for all samples. A specific gravity is maintained to be within the range of 1.023 g/cm\(^3\) to 1.025 g/cm\(^3\) similar to actual marine environment.

Adequate space is provided between all faces of each cube and the side of the curing tank to allow water to circulate adequately on the surfaces.

3. Results

3.1 Compressive Strength Test

Table 2 summarizes the averaged compressive strength of each sample.

| MIX   | Saturated wet cured (MPa) | Seawater cured (MPa) | Air dried (MPa) |
|-------|---------------------------|----------------------|-----------------|
| 1     | 20.96                     | 27.69                | 36.99           |
|       | 26.06                     | 34.51                | 45.36           |
|       | 25.50                     | 32.25                | 31.21           |
| 2     | 14.42                     | 17.94                | 32.60           |
|       | 15.23                     | 18.75                | 29.49           |
|       | 16.59                     | 21.02                | 28.40           |
| 3     | 16.39                     | 23.95                | 32.60           |
|       | 16.91                     | 27.45                | 37.15           |
|       | 17.54                     | 25.61                | 31.65           |
| 4     | 19.23                     | 21.58                | 48.96           |
|       | 22.76                     | 27.63                | 46.47           |
|       | 21.57                     | 33.81                | 40.61           |
| 5     | 15.68                     | 22.77                | 40.39           |
|       | 17.65                     | 26.17                | 40.24           |
|       | 17.94                     | 24.27                | 32.20           |

3.2 Water Absorption Test

Table 3 and 4 summarizes the averaged percentage water absorption taken at age of 28 days and 56 days respectively.

| b                      | Mix 1   | Mix 2   | Mix 3   | Mix 4   | Mix 5   |
|------------------------|---------|---------|---------|---------|---------|
| Saturated wet cured    | 3.05%   | 1.71%   | 1.38%   | 1.08%   | 1.49%   |
| Seawater cured         | 3.10%   | 2.13%   | 1.54%   | 1.53%   | 2.08%   |
| Air dried              | 3.33%   | 2.82%   | 1.90%   | 1.72%   | 2.58%   |

| b                      | Mix 1   | Mix 2   | Mix 3   | Mix 4   | Mix 5   |
|------------------------|---------|---------|---------|---------|---------|
| Saturated wet cured    | 1.96%   | 1.44%   | 1.26%   | 1.10%   | 1.37%   |
| Seawater cured         | 2.26%   | 1.79%   | 1.31%   | 1.46%   | 1.68%   |
| Air dried              | 2.99%   | 2.21%   | 1.77%   | 1.59%   | 1.99%   |
4 Findings and Analysis

4.1 Strength Development

4.1.1. Effect of varying curing conditions

From Figure 1 below, a trend can be observed in all the mixes whereby the 3 days and 7 days strength, is higher for air dried and seawater cured samples than that of the saturated wet cured samples. This contrasts with other experimental findings whereby strength of air-dried concrete is less than that of saturated wet cured in all ages. In this case, the strength development of air-dried samples might have increased due to initial placement of wet burlap. M I Retno suggested that the increase in early age strength for seawater was due to the high temperature subjected to the concrete in seawater \[^3\]. This is not the case in this study as both are kept at the same temperature range of 27°C to 30°C. Thus, the increase in compressive strength at early ages is more likely due to the presence of sodium chloride.

At 28 days, saturated wet cured samples are the strongest except OPC concrete (Mix 1). Air dried samples are weakest at 28 days whereas the seawater samples show an increase in strength, however, at a slower rate than the saturated wet cured samples. The difference in strength at 28 days between seawater cured and saturated wet cured samples is only about 1 to 3 MPa. At 56 days, the strength of air dried samples remained consistent or increase slightly due to lack of water resulting in slowing down or stopping of hydration. On the other hand, saturated wet cured and seawater cured samples increase in strength due to adequate supply of water to continue the hydration. The strength difference between the two curing is only slight, i.e. 2 to 3 MPa, which suggests that the type of curing water affects the overall strength development. Delayed ettringite formation may have occurred at later ages which degrades the strength of the seawater cured samples due to cracking in the microstructure.

![Figure 1](image-url)

Figure 1. Effect of varying curing condition on strength development.

The percentage of strength loss (%SL) at 56 days, in this context, is defined as the percentage difference in 56-day strength in comparison to saturated wet cured sample strength. All in all, the average %SL of seawater cured and air-dried samples at 56 days is 4.3% and 24.6% respectively. Thus, it can be deduced that seawater curing has no significant deteriorating effect on the strength.
unlike air drying which results in a high strength loss. For OPC concrete (Mix 1), a discrepancy may had occurred for the 28 days results resulting in a higher strength for the seawater cured sample. There is a difference of 8.37 MPa between OPC sample cured in plain water and that cured in seawater. Based on the raw results of the three samples, the three samples give consistent results and thus, this error might have been due to inconsistency in seawater curing which may had led to the optimization of the strength development for 28 days sample only.

4.1.2. Effect of decreasing water-binder ratio

The strength of all samples, regardless of the curing condition, is affected by the water-binder (w/b) ratio. From Figure 2, comparing between Mix 2, 3 and 4, a consistent trend can be observed whereby the strength increases with decreasing w/b ratio. Decreasing the w/b ratio by 0.1, increases the 28-days strength of the sample to approximately the same strength of the sample with higher w/b ratio at 56 days. For example, reducing the w/b ratio from 0.60 to 0.50 whilst maintaining the same percentage of PFA replacement results in a 28-days strength of 39.27 MPa for saturated wet cured sample. This is approximately the same as the 56-days strength of the sample with w/b ratio of 0.60 subjected to the same curing condition, that is 39.25 MPa. This trend is noticeable for all three mixes regardless of the curing conditions.

![Figure 2](image.png)

**Figure 2.** Effect of decreasing water-binder ratio on strength development.

At 56 days, the %SL of seawater cured samples for Mix 2, 3 and 4 are 4.7%, 3.6% and 3.1% respectively. Thus, reducing the w/b ratio not only increases the strength at all ages but also decreases the loss in strength at later ages. However, for air dried samples, the %SL for Mix 2, 3 and 4 are 23.1%, 25.4% and 22.6% respectively. Thus, the %SL do not follow the same trend as mentioned previously. This discrepancy may have been due to slight varying room temperature for different mixes as the duration of 56 days took place in different times. Comparing the three mixes with OPC concrete (Mix 1), the strength of PFA concrete up to 7 days is still less than OPC concrete even at w/b ratio of 0.40. This is due to the effect of inclusion of PFA whereby the early strength development is slowed down. Nonetheless, the early age strength of PFA concrete with w/b ratio of 0.4 is almost as strong as OPC concrete with w/b ratio of 0.6 at early ages. At 28 and 56 days, the strength of Mix 2
samples, for all curing conditions, is still less than OPC concrete. However, lowering w/b ratio to 0.50 and less significantly increases the later ages strength to exceed that of the OPC concrete.

4.1.3. Effect of PFA and silica fume as cement replacement.

Mix 1, 2 and 5 are of the same w/b ratio of 0.60. Therefore, the differences in strength is due to the varying cementitious content. From Figure 3, OPC Mix 1 samples have the highest strength at 3 to 7 days for all curing conditions. This indicates the effects of PFA which slows down the rate of strength development at the early ages in Mix 2 and Mix 5. However, samples of Mix 5 have a slightly higher strength than Mix 2 for all days. Thus, the 10% silica fume contributes to the increase in mass and density of the concrete and hence, gives a weak yet noticeable impact to the overall concrete strength. At 28 days, the strength of Mix 5 samples exceeds that of Mix 1 and 2 with an exception of that cured in seawater. However, this discrepancy may arise due to the slow early age strength development of PFA concrete and the faster strength development of OPC concrete in early ages. As seen in Figure 3, since the OPC concrete has reached a higher strength at early ages, the hydration continues to further increase the strength and results in a higher strength than PFA+SF concrete at 28 days.

Figure 3. Effect of PFA and silica fume as cement replacements on strength development.

In the case of PFA concrete (Mix 2), the strength is lower than OPC concrete (Mix 1) and PFA+SF concrete (Mix 5) due to very slow strength development at early ages. The slow hydration process is possibly due to the low cement content. It is only at 56 days that the strength exceeds that of OPC concrete (Mix 1). The pozzolanic effect of PFA which allows the continuous reaction of free lime, from hydration process, to form C-S-H gel and thus, making the concrete stronger at later ages.

The %SL for Mix 1, 2, and 5 subjected to seawater curing are 7.4%, 4.7% and 2.6% respectively. It can be observed that the OPC concrete exhibits a significant loss compared to concrete with PFA and PFA+SF. Therefore, PFA produces concrete of greater resistance to strength deterioration and silica fume further improves this resistance. However, the trend does not seem to follow for air dried concrete, the %SL for Mix 1, 2 and 5 are 26.1%, 23.1% and 25.6% respectively. Nonetheless, the PFA concretes still give lower strength losses than OPC concrete.
4.2 Water Absorption

Effect of varying curing conditions on water absorption at 28 days

|                        | MIX 1 | MIX 2 | MIX 3 | MIX 4 | MIX 5 |
|------------------------|-------|-------|-------|-------|-------|
| Saturated wet cured    | 3.05  | 1.71  | 1.38  | 1.08  | 1.49  |
| Seawater cured         | 3.1   | 2.13  | 1.54  | 1.53  | 2.08  |
| Air dried              | 3.33  | 2.82  | 1.9   | 1.72  | 2.58  |

**Figure 4.** Effect on water absorption at 28 days.

Effect of varying curing condition on water absorption at 56 days

|                        | MIX 1 | MIX 2 | MIX 3 | MIX 4 | MIX 5 |
|------------------------|-------|-------|-------|-------|-------|
| Saturated wet cured    | 1.96  | 1.44  | 1.26  | 1.1   | 1.37  |
| Seawater cured         | 2.26  | 1.79  | 1.31  | 1.46  | 1.68  |
| Air dried              | 2.99  | 2.21  | 1.77  | 1.59  | 1.99  |

**Figure 5.** Effect on water absorption at 56 days.

4.2.1. Effect of varying curing or exposure conditions

The percentage of water absorption (%WA) at 28 days is the highest for air dried samples and is the least for saturated wet cured samples. This indicates that the saturated wet cured samples are the least porous and thus, more durable. This is due to the continuous supply of water which allows the hydration to continue. The formation of C-S-H gel, as a result of hydration, results in closing of voids and forming a concrete with less pores. In the contrary, the air-dried samples are left to dry without provision of water and thus, the hydration is limited. This results in a less durable concrete with porous structure. On the other hand, samples in seawater are supplied with water to aid hydration. However, the seawater cured samples only show moderate %WA at 28 days which is more than the saturated wet cured samples. Thus, the type of water used for curing plays a role in the overall concrete development.

4.2.2. Effect of decreasing water-binder ratio

Comparing between Mix 2, 3 and 4 samples, the %WA decreases with decreasing w/b ratio for all curing conditions. Concrete with high w/b ratio creates more capillary voids created by movements of water. The size of voids increases in high w/b ratio mixes. In low w/b ratio, the size ranges from 10 to 50 µm whereas in high w/b ratio, pores are up to 3 to 5 µm.[6]

4.2.3. Effect of PFA and silica fume as cement replacement

Comparing between OPC concrete Mix 1 and PFA concrete Mix 2, the PFA gives a very noticeable reduction on %WA and thus, its porosity. Inclusion of PFA decreases the ability of the concrete cube to absorb water due to less pores in the structure regardless of the curing condition. However, the
curing condition determines the degree of improvement. Samples that are saturated wet cured showed a very drastic improvement whereby the %WA reduces significantly as compared to an equivalent OPC concrete that is subjected to same curing. There is a reduction of 1.34% for saturated wet cured samples whereas PFA concrete that is air dried and seawater cured only improves by 0.51% and 0.97% respectively. Similarly, this is due to hydration which is determined by the availability and type of the water. Comparing between PFA concrete Mix 2 and PFA+SF concrete Mix 5, Mix 5 samples showed a slight reduction in %WA in all curing conditions. Therefore, the silica fume decreases the pores more effectively than PFA due to its higher surface area resulting in a denser concrete. Thus, this affects the mobility of water particle in the concrete [5].

4.2.4. Comparison between 28 days and 56 days water absorption

The %WA at 28 and 56 days follow the same trend as described in the previous three subsections. However, all samples at 56 days are less porous due to the continuous hydration that took place during difference in ages. The curing conditions seem to not give any effect on the degree of improvement to the %WA as all samples for all curing conditions exhibit about the same degree of improvement except that of saturated wet cured OPC concrete. The %WA reduces very significantly from 3.05% at 28 days to 1.96% at 56 days. Despite the significant reduction, concrete with PFA (Mix 2) and PFA+SF (Mix 5) still have a lower %WA than the OPC concrete (Mix 1). Thus, the effect of PFA and silica fume to the porosity of the concrete is very noticeable producing a more durable concrete in later ages.

4.3 Relationship between Strength and Water Absorption

The strength increases with samples having low %WA. This trend is most evident in Mix 2, 3 and 4. Mix 4 samples having the highest strength is lowest %WA and vice versa for Mix 2. This can also be observed for the three curing conditions. Saturated wet cured samples having the highest strength results in lowest %WA and vice versa for air dried samples. This is because strength and %WA depend on the density, which is governed by curing and water-binder ratio. Higher density concrete would have higher strength due to higher mass and lower %WA due to less pores. However, this relationship between is not observed when comparing between PFA concrete Mix 2 and OPC concrete Mix 1. The PFA concrete having lower strength has higher %WA and vice versa for OPC concrete.

5 Conclusion

- Saturated wet curing is the most optimal curing method to achieve long-term strength and durability for both OPC and PFA concrete.
- Seawater curing results in higher strength of concrete at early ages up to 7 days for both OPC and PFA concrete and does not give significant strength degradation at later ages.
- Lower water-binder ratio results in higher strength concrete with low porosity for all ages
- Inclusion of 10% silica fume in PFA concrete improves the overall performance in strength and durability at all ages
- PFA, silica fume and low water-binder ratio give higher resistance to strength loss at later ages.

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