Physical-durable performance of concrete incorporating high loss on ignition-fly ash

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Abstract. This study investigates the feasibility of using raw fly ash with a high loss on ignition in concrete. The fly ash-free concrete samples were prepared with different water-to-binder (w/b) ratios of 0.35, 0.40, and 0.45, whereas the fly ash concrete samples were prepared with a constant w/b of 0.40 and with various fly ash contents (10%, 20%, and 30%) as a cement substitution. The physical properties and durability performance of the concretes were evaluated through fresh concrete properties, compressive strength, strength efficiency of cement, ultrasonic pulse velocity, and resistance to sulfate attack. Test results show that the w/b ratio affected the concrete properties significantly. The incorporation of fly ash increased the workability and reduced the unit weight of fresh concrete. In addition, the fly ash concrete samples containing up to 20% fly ash exhibited an improved strength at long-term ages. Further, all of the fly ash concrete samples showed a good durability performance with ultrasonic pulse velocity value of greater than 4100 m/s and a comparable sulfate resistance to the no-fly ash concrete.

1. Introduction

With the rapid development of construction industry, ordinary Portland cement concrete has become the most popular construction material in the world. Therefore, a large amount of cement is produced and consumed every year and thus the generation of carbon dioxide (CO²) during the production of ordinary Portland cement is consequently a serious environmental problem, causing the greenhouse effect and global warming. The production of ordinary Portland cement also consumes a significant energy and depletes the natural resources. Thus, it is necessary to reduce the emission of CO₂ and the disposal of industrial wastes, in which fly ash, a by-product from coal power plant, has been utilizing as a partial or full replacement of ordinary Portland cement in concrete instead of considering it as an industrial waste.

Although fly ash has been widely used in concrete for a long time, however, the results from previous studies varied depending on the source and characteristic of fly ash used. Wankhede and Fulari [1] stated that concrete with 10% and 20% fly ash replacing cement showed a better compressive strength than fly ash-free concrete, but the inverse result was observed with 30% fly ash content. Bansal et al. [2] reported that compressive strength of concrete containing 20% and 30% fly ash was about 11% and 19% higher than that of the no-fly ash concrete, respectively. Marthong and Agrawal [3] investigated the utilization of 10%, 20%, 30%, and 40% fly ash replacing cement in concrete. Their results exhibited that increasing the fly ash content yielded the reduction in compressive strength of concrete. However, the concrete with 20% fly ash content had a comparable compressive strength to the conventional concrete without
fly ash. Naik and Ramme [4] and Oner et al. [5] studied the use of up to 60% fly ash in concrete as a cement replacement. The results of these studies showed that the optimum fly ash replacement level was about 40%, at which showing the improved compressive strength. However, Siddique [6] indicated that concrete containing 40–60% fly ash had lower strength than normal concrete without fly ash. On the other hand, Li and Zhao [7] found that the combination of 25% fly ash and 15% granulated blast furnace slag enhanced both short- and long-term properties of concrete. Previous studies also reported that the workability of concrete increased with increasing the fly ash replacement level [1,3,4] and the use of fly ash in concrete also improved the resistance to sulfate attack [7,8].

Generally, the use of fly ash in concrete was found to have a positive effect on the concrete properties. However, the optimum dosages of fly ash used in concrete varied depending on the sources of fly ash and its quality. The selected fly ash in this study with the loss on ignition of less than 3.2% was used in most of the previous studies [4–8]. Thus, this study aims to investigate the feasibility of using raw fly ash with a high loss on ignition in concrete in order to fill the gap in the literature. The fly ash used in this study had the loss on ignition of 15.7%, which is much higher than the suggested value of lower than 6% of the ASTM C618 [9]. The effect of such fly ash on properties of both fresh and hardened concrete was investigated in the present study.

2. Materials and experimental works

2.1. Materials properties and mixture proportions

All of the materials used in this study were locally sourced from Thanh Hoa province, Vietnam. Nghi Son type-PC40 cement and class-F fly ash with the respective specific gravity of 3.12 and 2.16 were used as binder materials. Table 1 shows the chemical compositions of both cement and fly ash. It is noted that the fly ash used in this study is a raw material, which was taken from a local thermal power plant, with a high loss on ignition value of 15.7%. Natural sand and crushed stone, with properties as shown in Table 2, were used as fine and coarse aggregates, respectively. The superplasticizer (SP) with a specific gravity of 1.15 was used to obtain the desired workability of fresh concrete with less water. The ingredient proportions of all concrete mixtures are shown in Table 3. First three concrete mixtures (Group I) were designed with different w/b ratios of 0.35, 0.40, and 0.45. The group I samples used to examine the effect of the w/b ratio on physical and durable properties of the concrete. The last three mixtures (Group II) were designed with a constant w/b ratio of 0.40 and various fly ash replacement levels of 10%, 20%, and 30% cement. The group II samples used to investigate the effect of fly ash content on physical and durable properties of the concrete. In this study, all of the concrete mixtures were designed in accordance with ACI 211.91 [10] with controlling the amount of water less than 180 kg/m$^3$ for good durability as suggested by Hwang and Hung [11]. Nomenclature of the mixtures is described as follows: M35, M40, and M45 denote the respective w/b ratios of 0.35, 0.40, and 0.45. The following numbers (0, 10, 20 and 30) are the percentages of fly ash replacing cement in concrete mixtures.

| Compositions (wt. %) | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | Others | Loss on ignition |
|---------------------|--------|-------------|-------------|-----|-----|--------|-----------------|
| Cement              | 22.4   | 5.3         | 4.0         | 55.9| 2.8 | 4.4    | 2.0             |
| Fly ash             | 48.4   | 20.4        | 4.8         | 2.8 | 1.4 | 4.3    | 15.7            |

| Aggregate types     | Maximum size (mm) | Fineness modulus | Density (T/m$^3$) | Dry rodded weight (T/m$^3$) | Moisture content (%) | Water absorption (%) |
|---------------------|-------------------|------------------|------------------|----------------------------|----------------------|---------------------|
| Natural sand        | 5.0               | 2.87             | 2.62             | 1.50                       | 4.35                 | 1.08                |
| Crushed stone       | 12.5              | -                | 2.69             | 1.39                       | 0.25                 | 0.08                |
2.2. Samples preparation and test methods
Right after mixing, the properties of fresh concrete such as slump, unit weight were checked. The cylindrical concrete samples with a diameter of 100 mm and a height of 200 mm were prepared for testing of compressive strength, ultrasonic pulse velocity, and resistance to sulfate attack. In order to evaluate the resistance to sulfate attack, concrete specimens were fully immersed in 5% Na₂SO₄ solution right after demolding until the testing days. All of these tests were conducted at 3, 7, 14, 28, 56, and 91 days, with the reported results of each test are the average value of three concrete samples. Slump, compressive strength, and ultrasonic pulse velocity tests were performed in accordance with ASTM C143 [12], ASTM C39 [13], and ASTM C597 [14], respectively.

3. Results and discussion

3.1. Properties of fresh concrete
Fresh concrete properties of all mixtures are given in Table 4. As shown, the slump and fresh unit weight of fresh concrete mixtures ranged from 0–50 mm and 2470–2580 kg/m³, respectively. For the no-fly ash group, M45-0 mixture showed the highest slump, followed by M40-0 and M35-0. An inverse trend was observed in term of unit weight, in which M35-0 mixture exhibited the highest fresh unit weight, followed by M40-0 and M45-0. In this group, the slump of fresh concrete is closely related to the amount of water. So that when the w/b ratio increased, the amount of water increased. Thus, the workability of fresh concrete consequently improved. On the other hand, a low w/b ratio is associated with a higher amount of cement used in the concrete mixture. Hence, the higher unit weight of fresh concrete is mainly attributable to the higher specific gravity of cement compared with that of other ingredients in concrete mixtures.

Table 3. Mix proportions for the preparation of concrete samples.

| Sample ID | w/b  | Cement (kg/m³) | Fly ash (kg/m³) | Sand (kg/m³) | Stone (kg/m³) | Water (kg/m³) | SP |
|-----------|------|----------------|----------------|--------------|---------------|---------------|----|
| M35-0     | 0.35 | 514.1          | 0.0            | 985.2        | 751.1         | 175.5         | 5.1 |
| M40-0     | 0.40 | 450.0          | 0.0            | 1039.0       | 751.0         | 176.1         | 4.5 |
| M45-0     | 0.45 | 400.4          | 0.0            | 1082.1       | 751.8         | 175.7         | 4.0 |
| M40-10    |      | 402.4          | 44.7           | 1032.4       | 746.2         | 175.0         | 4.5 |
| M40-20    | 0.40 | 355.4          | 88.9           | 1025.9       | 741.5         | 173.9         | 4.4 |
| M40-30    |      | 309.1          | 132.5          | 1019.4       | 736.8         | 172.8         | 4.4 |

Table 4. Properties of fresh concrete mixtures.

| Sample ID | w/b  | SP dosage (kg/m³) | FA content (%) | Slump (mm) | Fresh unit weight (kg/m³) |
|-----------|------|-------------------|----------------|------------|--------------------------|
| M35-0     | 0.35 | 5.1               | 0              | 0          | 2580                     |
| M40-0     | 0.40 | 4.5               | 0              | 20         | 2550                     |
| M45-0     | 0.45 | 4.0               | 0              | 30         | 2530                     |
| M40-10    |      | 4.5               | 10             | 20         | 2530                     |
| M40-20    | 0.40 | 4.4               | 20             | 35         | 2500                     |
| M40-30    |      | 4.4               | 30             | 50         | 2470                     |

Table 4 also shows that increasing the fly ash replacement level resulted in an increase in workability and a reduction in unit weight of fresh concrete mixtures. The increased workability is mainly due to the spherical shape of fly ash particles. It is well known that the particle shape of cement and fly ash are irregular polygonal and spherical, respectively [15]. Therefore, owing to a spherical shape, the presence of fly ash reduced the friction between the aggregate and paste, thus improving the workability of fresh
Concrete. Moreover, due to the lower specific gravity of fly ash as compared with that of cement, the volume of fly ash paste is greater than that of the cement paste. The improvement of the plasticity and cohesion of the paste led to increasing the workability of fresh concrete. This finding is supported by the results of the previous studies [1,3,4]. On the other hand, the unit weight of fresh concrete reduced with increasing fly ash content in the concrete mixture. This is also due to the lower specific gravity of fly ash as compared with that of cement.

3.2. Compressive strength development

The effects of w/b ratio and fly ash content on compressive strength development of concrete are shown in Figure 1 and Figure 2, respectively. The 91-day compressive strength values of the M35-0, M40-0, and M45-0 mixtures were 39.5, 30.0, and 26.3 MPa, respectively. As the results, the concrete samples with lower w/b ratio had higher compressive strength values. With a similar amount of water, a concrete mixture with low w/b ratio used more amount of cement, resulting in a higher cement hydration rate and thus more hydration product as expressed in Equation (1), which contributed to a higher strength.

On the other hand, concrete samples incorporating 10% fly ash showed the highest compressive strength at the early ages (before 28 days), followed by the concrete samples with 0%, 20%, and 30% fly ash. However, after 56-day ages, concrete samples containing 10% and 20% fly ash exhibited the higher compressive strength than fly ash-free concrete. As mentioned in previous studies [1-7], the compressive strength of fly ash concrete was enhanced with the use of an optimum amount of fly ash. In case of using fly ash over the optimum level, a part of fly ash does not take part in the chemical reaction process. It mainly acts as a filler or fine aggregate rather than a supplementary cementitious material. The optimum amount of fly ash used in this study was around 20%, which is lower than that presented in previous studies [4-7] due to the poor quality of the raw fly ash used as aforementioned. The lower compressive strength at short-term and higher compressive strength at long-term are associated with the pozzolanic reaction of fly ash, which only significantly started after several weeks of the sample after casting. The continuous increase of compressive strength of fly ash concrete is due to the transformation of Ca(OH)$_2$ into the secondary C-S-H gels followed the Equation (2), which are the main carriers of loading in hardened concrete. Although M40-30 mixture with the use of 30% fly ash content showed the lowest compressive strength, its compressive strength was approximate 88% that of control mixture. All of the fly ash concrete mixtures showed a compressive strength value at 91 days of above 26.5 MPa. This finding further proved the feasibility of using the raw fly ash with a high loss on ignition in concrete.

Cement hydration:

\[
(C_3S, C_2S) + H_2O \rightarrow C-S-H + Ca(OH)_2
\]

Pozzolanic reaction:

\[
Ca(OH)_2 + SiO_2 \rightarrow C-S-H
\]

![Figure 1](image1.png)  
**Figure 1.** Effect of w/b on compressive strength development of the concrete samples.  
![Figure 2](image2.png)  
**Figure 2.** Effect of FA content on compressive strength development of the concrete samples.
3.3. Strength efficiency of cement
The strength efficiency of cement (SEC) is a yielded concrete compressive strength per kilogram of cement. So far, the amount of cement used in each mixture is associated with the production cost, energy consumption, and CO₂ emission during the production of cement and concrete. Thus, the SEC is an indicator for cost-effectiveness and environmental reduction of fly ash concrete mixtures. Figures 3 and 4 show the SEC in concrete samples prepared with various w/b ratios and fly ash contents, respectively. As can be seen from Figure 3, M35-0 mixture had the highest SEC value, followed by M40-0 and M45-0. This is due to the high volume of cement paste in the concrete mixture at the low w/b ratio, resulting in a greater hydration rate and thus more cement hydration products.

As shown in Figure 4, the 91-day SEC value of the M40 concrete mixtures with 0%, 10%, 20%, and 30% fly ash content were 0.067, 0.095, 0.092, and 0.084 MPa/kg/m³, respectively. The use of fly ash in concrete increased the SEC of about 26–42% as compared with the control concrete mixture (M40-0). This indicated that most fly ash particles participated in the pozzolanic reaction rather than existed as a filler or a fine aggregate. Fly ash particles reacted with calcium hydroxide to form C-S-H gel as expressed in Equation (2), thus improving the compressive strength of concrete. This also proved the cost-effectiveness when using this low-quality fly ash in concrete.

![Figure 3. Effect of w/b on strength efficiency of cement in concrete samples.](image1)

![Figure 4. Effect of fly ash content on strength efficiency of cement in concrete samples.](image2)

![Figure 5. Effect of w/b on UPV values of the hardened concretes.](image3)

![Figure 6. Effect of fly ash content on UPV values of the hardened concretes.](image4)

3.4. Ultrasonic pulse velocity
Values of the ultrasonic pulse velocity (UPV) is one of the indicators for durability of hardened concrete. The durable properties of concrete are often related to the structure of hardened concrete as the uniformity and the presence of voids and cracks. In general, concrete with a high value of UPV is associated with a denser structure and a good quality. Figures 5 and 6 show the results of the UPV test of concrete samples prepared with different w/b ratios and various fly ash replacement levels, respectively. As the results, the
UPV of all of the concrete samples increased continuously with the curing ages. Malhotra [16] previously reported that concrete with UPV value of higher than 3660 m/s was in good condition and durable. Thus, according to Malhotra suggestion, all of the concrete samples prepared in this study exhibited a good quality and durability with the UPV values of above 4100 m/s.

Figure 5 clearly shows that the 91-day UPV value of M35-0 mixture was the highest, followed by M40-0 and M45-0, whereas Figure 6 shows that increasing the level of fly ash replacement resulted in a decrease in UPV values. This is attributable to the amount of cement used in the mixtures as well as the density of concrete structure. The development of UPV value is due to the combined cement hydration and pozzolanic reaction took place within the system during the time.

3.5. Sulfate attack

The durability properties of concrete are greatly affected by the environmental condition and especially by the chemical attack. One of the most aggressive environmental agents is sulfate, which is popularly existed in soil, groundwater, and seawater in some areas. The compressive strength test results of concrete samples that fully immersed in 5% Na₂SO₄ solution are given in Table 5. As the results, the compressive strength values of all of the concrete samples in sulfate solution still kept increasing with the immersion time. Similar to the concrete samples cured in water, concrete in Na₂SO₄ solution with a lower w/b ratio showed a higher compressive strength and concrete with 10% and 20% fly ash content exhibited the higher compressive strength than that of the concrete without fly ash.

| Sample ID. | Compressive strength (MPa) |
|------------|-----------------------------|
|            | 3 days | 7 days | 14 days | 28 days | 56 days | 91 days |
| M35-0      | 20.64  | 26.07  | 28.41   | 29.40   | 31.17   | 32.51   |
| M40-0      | 13.35  | 19.03  | 22.24   | 24.80   | 25.89   | 27.02   |
| M45-0      | 11.73  | 13.90  | 15.80   | 20.24   | 23.07   | 23.91   |
| M40-10     | 15.93  | 17.94  | 24.53   | 29.68   | 32.38   | 35.15   |
| M40-20     | 11.19  | 13.19  | 18.36   | 22.18   | 26.45   | 29.87   |
| M40-30     | 9.58   | 12.43  | 16.15   | 18.91   | 21.27   | 23.63   |

Table 5. The compressive strength of concretes immersed in 5% Na₂SO₄ solution.

In order to evaluate and compare the development of compressive strength between concrete samples cured in water and the samples immersed in sulfate solution, the relative compressive strength values between these samples are plotted as shown in Figures 7 and 8. At the early ages, some samples obtained the relative strength of higher than 100%. This is due to the continuous cement hydration as expressed by Equation (1) or the reaction of fly ash with the liberated lime to form the C-S-H as expressed by Equation (2), and the reaction of sulfate ions with hydration products to form gypsum and ettringite as expressed by Equations
(3)–(6). The formation of C-S-H, gypsum, and ettringite lead to a denser structure and thus increasing the compressive strength of concrete under sulfate solution. However, after several weeks, the sulfate attack reaction become more dominant, the C-S-H was transformed to N-S-H and the formation of micro-cracks due to the expansion of gypsum and ettringite led to a reduction in concrete strength.

\[
\text{Na}_2\text{SO}_4.2\text{H}_2\text{O} + \text{Ca(OH)}_2 \rightarrow \text{CaSO}_4.2\text{H}_2\text{O} + 2\text{NaOH} \quad (3)
\]

\[
\text{Na}_2\text{SO}_4.2\text{H}_2\text{O} + \text{C-S-H} \rightarrow \text{CaSO}_4.2\text{H}_2\text{O} + \text{N-S-H} \quad (4)
\]

\[
\text{C}_4\text{AH}_{13} + 3\text{CaSO}_4.2\text{H}_2\text{O} + 14\text{H}_2\text{O} \rightarrow \text{C}_3\text{A}.3\text{CaSO}_4.32\text{H}_2\text{O} + \text{Ca(OH)}_2 \quad (5)
\]

\[
\text{C}_3\text{A}.\text{CaSO}_4.12\text{H}_2\text{O} + 2\text{CaSO}_4.2\text{H}_2\text{O} + 16\text{H}_2\text{O} \rightarrow \text{C}_3\text{A}.3\text{CaSO}_4.32\text{H}_2\text{O} \quad (6)
\]

As can be seen from Figure 7 that the reduction in strength of M35-0 mixture was the most significant with an approximation of 18% at 91-day of immersion. This is attributable to the high amount of cement, resulted in high potential shrinkage and micro-cracks. Whereas, the M40-0 and M45-0 mixtures showed a similar rate of reduction in concrete strength (around 10%) at 91-day of immersion. On the other hand, all of the concrete samples shown in Figure 8 presented the similar strength reduction rate at the later ages of the samples. As previously reported by Li and Zhao [7] and Torii et al. [8], the use of fly ash improved the resistance of concrete to sulfate attack. It is noted that those studies used selected fly ash with the loss on ignition less than 3.2%. However, the poor quality raw fly ash with a high loss on ignition of 15.7% was used in the present study. The fly ash concrete prepared for this study still exhibited a comparable ability of sulfate resistance compared with no fly ash concrete. This finding demonstrated the feasibility of using fly ash with a high loss on ignition in concrete under sulfate attack condition.

4. Conclusions

This research work investigates the physical and durable performance of concrete incorporating high loss on ignition-fly ash. Based on the experimental results, some main conclusions may be drawn as follows:

1. The workability of fresh concrete increased while the fresh unit weight reduced with increasing the fly ash replacement level.
2. The compressive strength of concrete increased with up to 20% fly ash content in the mixture, with a maximum compressive strength value of 41.3 MPa. In addition, the fly ash concrete had 26–42% higher strength efficiency of cement than that of the fly ash-free concrete.
3. All of the fly ash concrete mixtures showed the good durability performance with the UPV values of above 4100 m/s and a comparable sulfate resistance to the no-fly ash concrete.
4. The physical-durable performance of concrete was also significantly affected by the w/b ratio as higher w/b ratio resulted in higher workability, however, lower values of fresh unit weight, SEC, UPV, and compressive strength of the concrete.
5. The results of the present study further demonstrate a high possibility of using of fly ash with a high loss on ignition in the production of concrete.

5. References

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