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Comparative performance of conventional OPC concrete and HPC designed by densified mixture design algorithm

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Abstract. This experimental study evaluated the performance of normal ordinary Portland cement (OPC) concrete and high-performance concrete (HPC) that were designed by the conventional method (ACI) and densified mixture design algorithm (DMDA) method, respectively. Engineering properties and durability performance of both the OPC and HPC samples were studied using the tests of workability, compressive strength, water absorption, ultrasonic pulse velocity, and electrical surface resistivity. Test results show that the HPC performed good fresh property and further showed better performance in terms of strength and durability as compared to the OPC.

Keywords: Conventional OPC concrete, High-performance concrete (HPC), Densified mixture design algorithm (DMDA), Compressive strength development, Durability.

1. Introduction
Concrete is one of the major materials that used with a large quantity of many construction activities. Recently, the design consideration for concrete proportion has not only focused on short-term strength but also emphasized on long-term performance (strength and durability). It is reported that the amount of cement and mixing water used in the concrete mixture is closely associated with many problems occurred during its life-cycle. Therefore, the cement and water content in the mixture should be limited in order to maintain the durability of the concrete [1−3].

High-performance concrete (HPC) is the concrete with good workability and mechanical properties and high resistance ability to chemical attack as compared to conventional concrete [4]. The incorporation of various supplementary cementitious materials, such as fly ash (FA), ground granulated blast-furnace slag (GGBS), rice husk ash (RHA), etc. in the HPC mixture has been studied by many researchers with a general result showing an improvement of concrete performance in both fresh and hardened stages [4−6]. The application of the DMDA, which was developed by the Hwang’s research group at National Taiwan University of Science and Technology in the HPC mix design is promoted in this study. In DMDA, the maximum density of the concrete can be obtained by well packing all solid particles with different sizes to a dense structure. Thus, the DMDA-concrete is expected to have high strength and good durability. The DMDA has been successfully applied to design the concrete that used for many projects in Taiwan [4, 7, 8]. An evaluation on engineering properties and durability of the HPC in comparison with those of the conventional OPC concrete will be performed and discussed in this study.

2. Materials and experimental works
2.1. Materials
The physical properties and chemical compositions of binder materials used in this study are given in Table 1. For the preparation of concrete samples, natural crushed sand (fineness modulus 3.0, density 2640 kg/m$^3$, and water absorption 1.0%) and natural crushed stone (12 mm maximum size, density 2670 kg/m$^3$, and water absorption 0.7%) were used as fine and coarse aggregates, respectively. The workability of fresh concrete was controlled using type-G superplasticizer (SP) with a specific gravity of 1.34. Local tap water was used as mixing water.

| Table 1. Characteristics of source materials. |
|-----------------------------------------------|
| **Items**                                   | **Cement** | **GGBFS** | **FA** |
| Physical properties                         |            |           |        |
| Specific gravity                            | 3.15       | 2.92      | 2.26   |
| Mean particle size (μm)                     | 19.1       | 8.8       | 21.8   |
| Specific surface area (m$^2$/g)             | 0.78       | 1.68      | 0.66   |
| Chemical compositions (wt.%)                |            |           |        |
| SiO$_2$                                     | 20.0       | 39.1      | 64.1   |
| Al$_2$O$_3$                                  | 4.2        | 13.0      | 22.1   |
| Fe$_2$O$_3$                                  | 3.1        | 0.2       | 5.6    |
| CaO                                         | 62.4       | 37.5      | 2.7    |
| MgO                                         | 4.1        | 7.1       | 0.9    |
| Na$_2$O                                     | 0.3        | -         | 0.8    |
| K$_2$O                                      | 0.4        | 0.2       | 1.3    |
| Others                                      | 3.6        | 2.0       | 1.9    |

| Table 2. Mixture proportions for the preparation of concrete samples. |
|-----------------------------------------------|
| **Mixture** | **w/b** | **Concrete ingredients proportion (kg/m$^3$)** | **OPC** | **GGBFS** | **FA** | **Sand** | **Stone** | **SP** | **Water** |
| OPC       | 0.35    | 509.5                                           | -       | -         | -      | 751.0    | 994.0     | 1.7    | 180.2     |
| HPC       | 0.35    | 265.6                                           | 103.3   | 93.3      | 854.5  | 942.0    | 2.8       | 160.4   |

2.2. Mix design concept and ingredient proportions
In this study, the mix proportions of conventional OPC concrete and HPC were designed in accordance with the traditional ACI method and the DMDA technology, respectively. The Hwang’s research group at the National Taiwan University of Science and Technology developed the DMDA from the hypothesis that physical properties of a concrete will be optimum when its physical density is high. Thus, the DMDA uses FA as a filler to fill the voids between aggregate particles and hence increases the density of the aggregate system. Additionally, the DMDA also uses FA and GGBFS as pozzolanic materials that may consider as a cement substitution. Hence, the cement paste of DMDA mixture can be reduced as compared to that of ACI mixture. It is important to note that the following criteria should be controlled in the DMDA mix design in order to guarantee the strength and long-term durability of the concrete: (i) water-to-cement ratio is greater than 0.42 (to prevent autogenous shrinkage or chemical contraction due to the cement hydration and/ or pozzolanic reaction); (ii) mixing water is less than 160 kg/m$^3$ (to ensure the volume stability and prevent the large drying shrinkage); and (iii) using as less cement as possible (to reduce the harmful expansion or swelling due to the alkali-aggregate reaction or sulfate attack). The detailed mix design procedures, as well as the design consideration, for both the ACI and DMDA methods are described in references [9] and [3], respectively. The ingredient proportions for these concrete mixtures are shown in Table 2.

2.3. Samples preparation and test methods
The measurement of fresh concrete workability was performed in accordance with ASTM C143. The cylindrical concrete samples with a diameter of 100 mm and a height of 200 mm were prepared for the
tests of compressive strength, ultrasonic pulse velocity (UPV), and electrical surface resistivity (ESR). The compressive strength test was conducted at 7, 14, 28, and 56 days in accordance with ASTM C39. Whereas, the UPV and ESR values were measured at 28 and 56 days by following the ASTM C597 guidelines and using a four-point Wenner array [10], respectively. The water absorption capacity (WAC) of the concrete samples was also determined at 28 and 56 days in accordance with ASTM C1585 using samples with a diameter of 100 mm and a height of 50 mm.

3. Results and Discussion

3.1. Workability of fresh concrete

Workability of fresh concrete including slump, slump flow spread, and flow time is presented in Table 3. Different SP dosages (as shown in Tables 2 and 3) were used to achieving the desired slump value of greater than 200 mm. Table 2 shows that the OPC concrete uses more cement, therefore, it normally requires more water in order to produce a certain workability because the flocs of cement particles trap a part of mixing water. Whereas, the HPC uses more SP to limit the water content, one of the design considerations of the DMDA as aforementioned, but still remaining a similar workability as that of the OPC. Additionally, the HPC incorporating FA with spherical particles may significantly reduce the friction of the particles system, resulting in a greater workability. As the results, both the OPC and HPC mixtures exhibited good flowability without bleeding or segregation.

Table 3. Workability of fresh concrete mixtures.

| Mixture | w/b | SP (%) | Slump (mm) | Slump flow (mm) | Flow time (sec.) |
|---------|-----|--------|------------|-----------------|-----------------|
| OPC     | 0.35| 0.33   | 225        | 510             | 9               |
| HPC     | 0.61| 245    | 580        |                 | 17              |

3.2. Compressive strength development

Compressive strength is one of the important indicators of concrete quality. In this study, the compressive strength development of the concrete samples is presented in Figure 1. As expected, the compressive strength increases with curing age of the concrete samples. At 28-day age, the compressive strength values of the OPC and HPC were 42.5 and 41.4 MPa, respectively. After 56 days of curing, the compressive strength of the OPC and HPC reached the values of 44.1 and 47.9 MPa, respectively. In addition, Figure 3 clearly shows that the OPC obtained higher strength than the HPC at the early age. However, the reversed trend was observed at the later age of the concretes. The compressive strength of the 56-day-old HPC was approximate 1.1 times higher than that of the OPC at the same age. Moreover, the rate of strength increment (from 28 days to 56 days) of the HPC was 15.7%, which was much greater than that of
the OPC (only 3.8%). The higher long-term strength attributed to the positive effects of both aggregates packing and hydration of both cement and pozzolanic materials (FA and GGBFS) at later ages [11].

3.3. Water absorption capacity
The water absorption capacity (WAC) of all concrete samples is presented in Figure 2. The WAC of the OPC at 28 days and 56 days were 4.8 and 3.2%, while that of the HPC at the respective ages was 4.5 and 2.5%. Thus, the WAC of the 28-day-old and 56-day-old OPC samples was 6.7 and 28.0% higher than that of the HPC at the respective ages. The test result of WAC supported the development in compressive strength of concrete as the WAC decreased with the increased compressive strength along with its curing age. Such reduction in WAC is primarily due to the decrease in the porosity of the concrete samples.

3.4. Ultrasonic pulse velocity
The value of ultrasonic pulse velocity (UPV) is considered as an indicator of concrete durabilities such as porosity and permeability. A higher UPV value is generally associated with a denser structure of concrete, indicating a good concrete quality. The UPV values of all tested samples are presented in Figure 3. As can be seen from the figure, the UPV value of both the OPC and HPC increased with the age of the sample. Moreover, the recorded UPV values for the HPC at 28-day and 56-day ages were approximate 1 and 3% higher than those of the OPC, respectively. The OPC had a higher porosity, which is indicated by the high WAC as mentioned above, than the HPC. Therefore, the UPV value of the OPC is lower than that of the HPC because of the increased travel time of the pulse through the samples [11]. Overall, the UPV values of all concretes were significantly higher than 3500 m/s after 28 days. Thus, these samples exhibited good quality and durability [12], in which the HPC exhibited a better durability performance, indicated by higher UPV value than the OPC.

3.5. Electrical surface resistivity
Electrical surface resistivity (ESR) is another indicator of concrete durability [13] as higher ESR associated with the lower potential of chloride penetration [3]. Figure 4 shows the test results of electrical surface resistivity (ESR) of all concrete samples used in this investigation. Similar to compressive strength development and UPV, the ESR was found to be increased with concrete ages. As the results, the OPC and HPC had a respective ESR value of 5.8 and 20.3 kΩ.cm at 28 days and reached to 10.1 and 37.8 kΩ.cm after 56 days of curing. It is suggested by some researchers that concrete with ESR value of greater than 20 kΩ.cm exhibited an excellent anti-erosion ability [13–15]. Thus, the corrosion may not occur in the HPC. Moreover, the ESR values of the HPC at 28-day and 56-day ages were 3.5 and 3.7 times higher than those of the OPC, respectively. Therefore, the HPC had better corrosion endurance than the OPC.

4. Conclusions
The present study evaluates the performance of the conventional OPC concrete designed by ACI method and the HPC designed by DMDA. Based on the test results, the following conclusions may be drawn:

1. The fresh HPC mixture with the use of SP and the incorporation of FA provided a better workability than the OPC one.
2. The HPC designed with less cement and water contents obtained higher long-term compressive strength and lower water absorption rate than the OPC.
3. The ESR of the OPC was under the threshold limit value of 20 kΩ.cm, whereas that of the HPC was above this limit. On the other hand, the UPV values of these concrete samples significantly reached above 3500 m/s. Thus, the HPC can be considered to be more durable and good corrosion endurance than the OPC.
4. The results of this study promote the application of the DMDA in the mix proportion design of the HPC in order to achieve better performance of the concrete.

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