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# An approach to optimizing mix design for properties of high-performance concrete

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**Abstract**

Laboratory and in situ test results reveal that the densified mixture design algorithm (DMDA) can be used to produce high-performance concrete (HPC) of good durability and high workability. The water-to-solid (W/S) weight ratio is known to have significant influence on the volume stability of concrete. This paper discusses strength of $f'c$>56 MPa, slumps of 230–270 mm, effect of the W/S ratio on the development of strength and durability of HPC at both fresh and hardened states. In addition to the water-to-cement (W/C) ratio and water-to-binder (W/B) ratio, the W/S ratio also has a significant effect on the performance of concrete. The utilization of fly ash and slag has been proven beneficial to the rheology of HPC in enhancing its strength development and durability.


*Keywords:* Densified mixture design algorithm; Durability; High-performance concrete; Water-to-solid weight ratio

## 1. Introduction

Concrete that does not have a good workability is not high-performance concrete (HPC). Therefore, much effort has been devoted to the research of mix designs aiming to produce concrete of high flowability and workability during the fresh stage as well as strong and durable once it hardens. Data obtained from existing publications indicate that high-strength concrete made with a low water-to-binder (W/B) ratio requires a large amount of cement in the mixing process [1,2] and may cause severe creep and drying shrinkage [3]. Moreover, the normal weight concrete that uses high cement content will increase the quantity of water needed, which will in turn lead to detrimental results including bleeding and segregation in the concrete as well as weak interfaces between granular materials [4,5]. Therefore, how to obtain high workability with low water and cement content merits further investigation. It is generally known that high cement content will produce concrete of high strength [6]. Therefore, the solution to the above-mentioned problem seems to lie in concrete mix designs.

To achieve high strength and workability while reducing creep and shrinkage and low durability, Chang et al. [2] suggested to use water-reducing agent, superplasticizers and pozzolanic materials in the mix designs. The chemical reactivity of superplasticizers lasts only for 60 min [7,8]. While pozzolanic materials, such as fly ash, blast-furnace slag or rice husk ash, are used, there is a risk of insufficient early strength of concrete. Therefore, how to minimize or eliminate the adverse effects of the materials used in the mixture design to increase durability is the main focus of our research.

This paper follows the concept of maximum density [9–13], with the assumption that the best engineering properties will be achieved when the mixing materials are most densely packed. The gel generated from the hydration of cement and from the chemical reaction of pozzolanic materials can also contribute to satisfactory early strength and long-term durability of the concrete [2,14,15].

## 2. Research significance

Pozzolanic materials are crucial to HPC as far as flowability is concerned [16]. In addition to lowering the heat of hydration, the use of fly ash and slag can improve the workability, plasticity, water tightness, resistance to sulfate and seawater attack [17]. In this study, the mixture design of HPC emphasizes the amount of binder used. A higher content of pozzolanic materials implies that less cement is

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needed. Controlling the water content and the water-to-solid (W/S) ratio is an indirect approach to stabilizing the volume, thus ensuring greater durability achieved in the mixture proportion of concrete.

## 3. Background

### 3.1. Densified mix designs

Traditional ACI mixture proportion algorithm [4] has given workability the highest priority followed by strength, durability and economy. To achieve higher workability, a larger amount of water will be required, thus calling for a higher cement content. However, such mixture proportion will induce risks of concrete creep. Large-scale deformation due to autogenous shrinkage will occur when the water-to-cement (W/C) ratio is $< 0.42$ due to the hydration of $C_3S$. Therefore, a low paste mixture proportion should be considered, making use of the highest density, the lowest W/B ratio and the maximum unit weight to obtain HPC of the best quality. The relationship among the volume of concrete paste ($V_p$), the volume of void aggregates space ($V_v$), the surface area of aggregate ($S$) and the thickness of lubricant paste ($t$) can be expressed as Eq. (1) [17].

$$V_p = V_v + St \tag{1}$$

$$N = V_p/V_v = 1 + (St)/V_v \tag{1a}$$

As seen from the above equation, to decrease the paste volume, the void space between the aggregates should be reduced. In other words, the paste volume can be decreased by a better mixture proportion of the aggregate [4] or by packing the mixing materials more densely [13]. In addition, the surface area of the aggregate ($S$) should also be reduced by increasing the maximum size of aggregate ($D_{max}$) [14]. However, this will affect adversely the interface bonding between the aggregate and the cement paste. According to ACI 318 [7], coarse aggregate with smaller $D_{max}$ is required to increase the strength of concrete. Therefore, it is of paramount importance to select an optimum paste volume and aggregate size to balance the need of both workability and durability. A possible alternative is to reduce the amount of lubricant paste used. This can be achieved by employing high-range water-reducing admixtures (HRWRA) that ensures sufficient lubrication even with a low paste content. In this way, granular components of the aggregate can easily move into a close packing position with minimal energy required, thus providing high workability.

### 3.2. Granular materials

Aggregate occupies up to 50–75% of the concrete volume. Therefore, controlling the aggregate mixture proportion will help to minimize the volume of void space, thereby achieving higher strength and better workability. A better gradation of the solid materials will provide a better mixture proportion of the concrete [12,13,18]. This is because the packing of the granular materials can influence greatly their macromechanical properties [5,12,19,20]. In other words, the denser the granular materials, the smaller the volume of void space will become. In addition, there will be more aggregate contact points giving rise to higher density, resulting in greater strength achieved [12,13,21]. Furthermore, with the same W/C ratio, lesser cement paste is needed when the aggregate is more densely packed, implying that a smaller amount of water is required. This can in turn reduce the occurrence of weak interface between the aggregate and the cement paste [4,5], thus enhancing the overall strength of the concrete [22]. Although densely packed aggregate should in theory increase concrete workability [13], the higher aggregate content will increase the friction between granular materials, thereby reducing the workability. This may bear some negative effects on the actual strength of concrete [5,22]. Hence, how to strike a balance between the packing density and the concrete strength remains an important issue.

### 3.3. Chemical agents

Traditional ACI mixture proportion adjusts workability by changing the amount of water in the mixture. Care must be taken because a high water content may have detrimental effects on concrete of high flowability [4]. Effective use of chemical agents such as water-reducing agent [2,7] can improve the flowability of concrete at low W/C ratios. High flowability reduces the friction between the densely packed granular materials. The addition of high-range water-reducing agent enables the granular materials of the freshly mixed concrete to slide easily along the surface, thereby reducing the flowing resistance and increasing the workability [7,8]. Surface dispersants such as the ASTM C494 Types F and G high-range water-reducing agent and other retarding agents have been proven to increase workability [2]. They induce mutual electrostatic repulsion at the interface, thereby decreasing the thickness of the water membrane in the adsorption and diffusion layers of the fresh concrete. As a result, the water content will be reduced. On the other hand, high-range water-reducing agents in large dosage may cause bleeding and segregation of the concrete and create larger slump loss, thus weakening its efficiency. These obstacles remain to be overcome.

### 3.4. Pozzolanic materials

Use of pozzolanic materials can decrease the amount of cement required, thus reducing the heat of hydration [22] and the occurrence of creep and shrinkage in concrete due to the high cement content. Moreover, pozzolanic materials can increase the consistency of the concrete paste. Through the pozzolanic reaction and void filling, the density of concrete can be increased. This will in turn improve the interface of the materials, thereby enhancing the strength of the concrete [5,10,23,24]. However, care should be taken in the application of pozzolanic materials to avoid any adverse effect on the early strength of concrete [10].

### 3.5. Cement paste and aggregate interaction

Cement paste is required for binding the inert aggregate and for filling the void space between the aggregate. In this way, the stress concentration can be reduced, leading to an increase in strength. Under the assumption that cement paste of the same W/C ratio should have the same binding strength, too much cement paste should be avoided to minimize the formation of microcracks in concrete [25]. Nevertheless, if too little cement paste is used, void and honeycombs will appear, causing detrimental effects on the concrete strength [22]. Again, the optimum amount of lubricants and cement paste is the key to avoiding excessive void, thus producing HPC of good strength.

The mixture design method used in this study follows the densified mixture design algorithm (DMDA) [25]. The main materials used include cement, slag, fly ash and aggregate. Their chemical and physical properties required for the mixture design are listed in Tables 1 and 2.

Table 1
Chemical analysis and physical properties of cement, slag and fly ash

| Items | | Cement (wt.%) | Slag (wt.%) | Fly ash (wt.%) |
|---|---|---|---|---|
| Chemical ionization | $SiO_2$ | 22.0 | 34.9 | 51.2 |
| | $Al_2O_3$ | 5.6 | 13.6 | 24.3 |
| | $Fe_2O_3$ | 3.4 | 0.5 | 6.1 |
| | CaO | 62.8 | 41.8 | 6.3 |
| | MgO | 2.6 | 7.2 | 1.6 |
| | $SO_3$ | 2.1 | 1.7 | 0.6 |
| | Free CaO | 1.1 | – | – |
| | $TiO_2$ | 0.5 | – | – |
| | $Na_2O$ | 0.4 | – | – |
| | $K_2O$ | 0.8 | – | – |
| | Loss on ignition (LOI) | 0.5 | 0.3 | 0.9 |
| | Insoluble residue | 0.1 | – | – |
| Potential clinker minerals | $C_3S$ | 40.1 | – | – |
| | $C_2S$ | 32.8 | – | – |
| | $C_3A$ | 8.9 | – | – |
| | $C_4AF$ | 10.5 | – | – |
| Physical properties | Fineness (g/cm$^2$) | 2970 | 4350 | 3110 |
| | Density (g/cm$^3$) | 3.15 | 2.87 | 2.21 |
| | Setting time, I.S (h:min) Vicat | 4:37 (W/C = 0.47) | – | – |
| | Setting time, F.S (h:min) Vicat | 8:22 | – | – |
| | Retention on 325 sieve (%) | – | – | 8.0 |

Table 2
Basic properties of aggregates

| Properties | Coarse aggregates | Fine aggregates (sand) |
|---|---|---|
| Specific gravity (SSD) | 2.67 | 2.66 |
| Specific gravity of oven dry (OD) | 2.65 | 2.64 |
| Water absorption (%) | 0.81 | 1.96 |
| Max size $D_{max}$ (mm) | 12.7 | 4.75 |
| Fineness modulus | 6.35 | 2.95 |
| Unit weight (kg/m$^3$) | 1576 | 1649 |

## 4. Test program

The objective is to optimize mix designs for producing HPC of high workability and high strength without bleeding and segregation and without developing creep and shrinkage (Table 3).

### 4.1. Materials

Materials used in this study include the ASTM C150 compliant Type I ordinary Portland cement, class F fly ash from Taiwan Power, blast-furnace slag from China Steel (see Table 1), domestic river sands and crush stones rinsed according to ASTM C33 (see Table 2) and Type 1000 superplasticizer which complies with the ASTM C494 Type G admixture.

### 4.2. Test variables

Two series of test programs were conducted to investigate the various effects on HPC at both fresh and hardened states. In the first series, the W/B ratio was controlled at

Table 3
Mix proportions of HPC

| $N$ | W/B | W/C | W/S (%) | Materials (kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Water[a] | SP[a] (wt.%) | Cement | Fly ash | Slag | Sand | Stone |
| 1.2 | 0.48 | 0.98 | 7.8 | 162 | 2.8 | 175 | 176 | 9 | 923 | 899 |
| 1.4 | 0.48 | 0.85 | 9.0 | 187 | 1.5 | 226 | 167 | 12 | 877 | 854 |
| 1.6 | 0.48 | 0.78 | 10.2 | 212 | 0.7 | 277 | 158 | 15 | 831 | 809 |
| 1.8 | 0.48 | 0.73 | 11.3 | 238 | 0.2 | 328 | 149 | 17 | 784 | 764 |
| 2.1[b] | 0.48 | 0.48 | 11.5 | 240 | 0 | 500 | 0 | 0 | 791 | 791 |
| 1.6 | 0.4 | 0.61 | 9.2 | 192 | 1.2 | 324 | 158 | 17 | 831 | 809 |
| 1.6 | 0.32 | 0.47 | 8.1 | 166 | 2.5 | 384 | 158 | 20 | 831 | 809 |

$N$, $V_p/V_v$, $V_v$; the least void; $N$, magnification factor of binder content.
B, binder including cement, fly ash and slag.
S, solid materials including weight of binder and aggregate.
SP, Type 1000 superplasticizer ASTM C494 HRWRA, naphthalene based.
SP (%), weight of superplasticizer to binder content ratio.
W, clean water.
[a] Includes water in the superplasticizer.
[b] ACI 211.4R mix proportions.

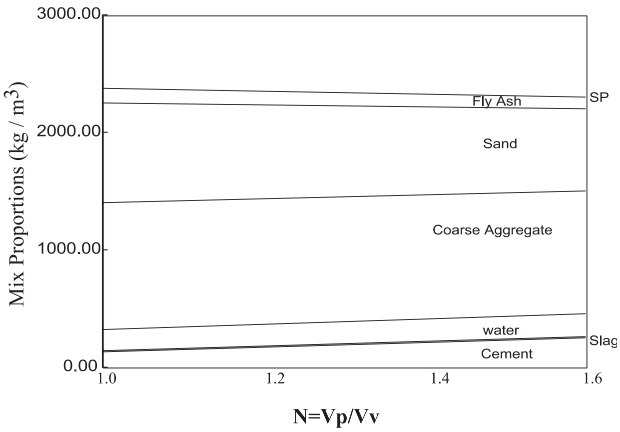


Fig. 1. The relationship between paste amounts and mix proportions at W/B = 0.32.

0.48, while the amount of water and binder used was taken as a variable. Then, in the second test, the binder content was kept constant while the following values were assumed for the W/B ratio: 0.28, 0.30, 0.32, 0.40 and 0.48. The mix proportions were developed according to the DMDA, which calculates the least void volume was adopted [1–3,25]. The least volume of voids between aggregates depends on the aggregate gradation. The least possible paste amount ($V_p$) is estimated. First assume that the amount of paste that coats the aggregate is *St*, where *S* is surface area of aggregate and *t* is thickness of lubricant, and then calculate all material proportion ($W_j$), where $W_j$ is the proportion by weight of the different materials. Different blend ratios of sand and fly ash were measured to obtain the maximum unit weight according to ASTM C29, C127. The unit weight measurement was also conducted for the coarse aggregate to determine the maximum substitute ratio of the blended fly ash to sands. The maximum unit weights of fly ash, sands and coarse aggregates thus obtained were used as the basic composition of the HPC [3,25]. The heat of hydration of fly ash and slag was also studied.

### 4.3. Methods

#### 4.3.1. Calculation of mix proportions

The mix proportion has been plotted in Fig. 1. Concrete materials was calculated according to the ACI 211.4R "Guide for selecting properties for high-strength concrete with Portland cement and fly ash" [16] and the properties of basic materials and mixture proportion of HPC suggested by Chang et al. [3]. The optimal amount fly ash to fill aggregate voids is determined [3,13]. Then, coarse aggregate is added to the mixture in proportion to the maximum unit weight. The ratio of fly ash to both fine and coarse aggregates of the maximum unit weight can then be obtained to calculate the void volume ($V_v$). When cement paste content equals to void volume ($V_p = V_v$), it indicates that all the void space is entirely filled with cement paste.

#### 4.3.2. Inspection on concrete properties

The slump test was performed according to the CNS 1176, Method of Slump Test for Concrete. The compressive strength was tested according to the CNS 1232, Method of Test for Compressive Strength of Cylindrical Concrete Specimens. The ultrasonic wave measurement was conducted according to the ASTM C597 using ultrasonic devices to measure the sound waves through concrete cylinders before the test. Durability data are available and these are evaluated using concrete specimens of 10 cm ø × 20 cm height on which the concrete electrical resistivity was measured with a DC resistivity gauge. Singly reinforced concrete beam specimens (12 × 20 × 80 cm), the most represented specimens, were tested for the content of chloride penetration charge. The permeability index before and after corrosion was measured to evaluate the anticorrosion efficiency of HPC. The data collected from the tests are used as the strength, durability [26] and homogeneity indices of the concrete.

## 5. Results and discussion

### 5.1. Properties of fresh HPC

From the laboratory tests, the initial slump of the HPC is measured to be 255 mm and the slump flow is 620 mm. After 45 min, the slump reduces to 250 mm and the slump flow becomes 570 mm. The unit weight of the fresh HPC is 2439 kg/m$^3$, which is much higher than 2300 kg/m$^3$ of the general plain concrete. Fig. 2, with paste amounts ($V_p$) varying from 1.2 to 2.1 N, shows that flowage is improved with higher $V_p$. The first torque value is given by the rheological friction. The tests were made on fresh HPC. High pumping pressure is required in the beginning to overcome the friction between the tube and the concrete. When the resistance is eliminated and a smooth sliding

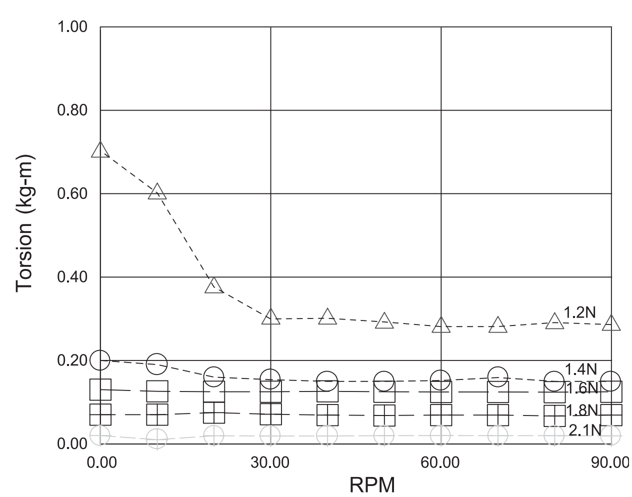


Fig. 2. The rheology of fresh HPC.

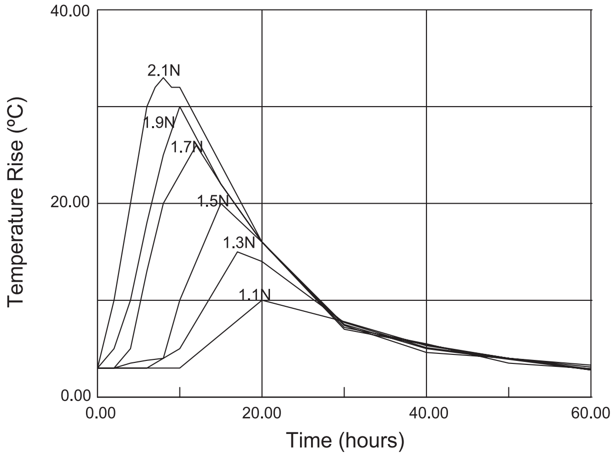


Fig. 3. The influence of paste content on the calorimetric curve.

interface is formed, the pumping pressure can then be decreased. A stable pumping pressure lower than the initial one indicates that the HPC has a good flowability characteristic. Fig. 3 shows the calorimetric curve of the fresh HPC, which clearly indicates that heat evolution is closely related to the amount of paste used and cement content. On the contrary, the higher the fly ash and slag content is, the lower the peak of the heat evolution curve will be.

## 5.2. Properties of hardened HPC

The strength development of the HPC is shown in Fig. 4. As can be seen, at the early stage (< 28 days), the HPC with less paste but some amount of binder used appears to have smaller compressive strength due to the presence of a large amount of fly ash and high dosage of superplasticizers. However, after 56 days, all mixtures reach the required strength, and after 180 days, they all show a similar strength because the total amount of binder used is the same. The fly ash and slag produce HPC with finer pores and a denser

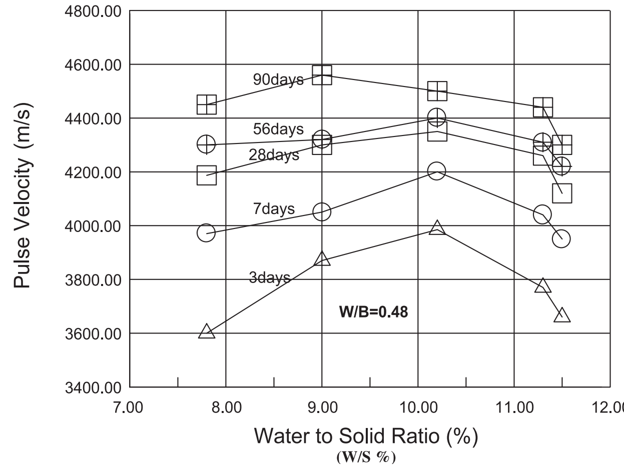


Fig. 5. The relationship between pulse velocity and W/S ratio at W/B = 0.48.

structure, thus improving the interface strength. Consequently, the strength of HPC containing fly ash can be regarded as the superposition of the effects of both cement hydration and pozzolanic reaction. With respect to the strength of HPC, fly ash actually plays the role of aggregate densifying and boundary strengthening.

## 5.3. Pulse velocity

The relationship between pulse velocity and W/S ratio at different ages for each mixture with a fixed W/B ratio of 0.48 is plotted in Fig. 5. As can be seen, with the exception of certain higher pulse velocities observed at 3 days, pulse velocities from all ages are lower than that of the HPC with W/S ratio ranging from 9% to 10%. This suggests that structural defects may slow down the pulse velocity under most W/S ratios and cement content, be it high or low. Fig. 6 shows the ultrasonic pulse velocity for various W/B ratios

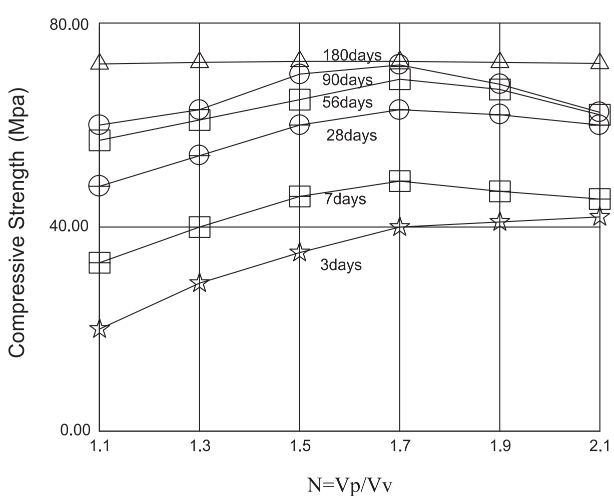


Fig. 4. The influence of paste content on the compressive strength of HPC.

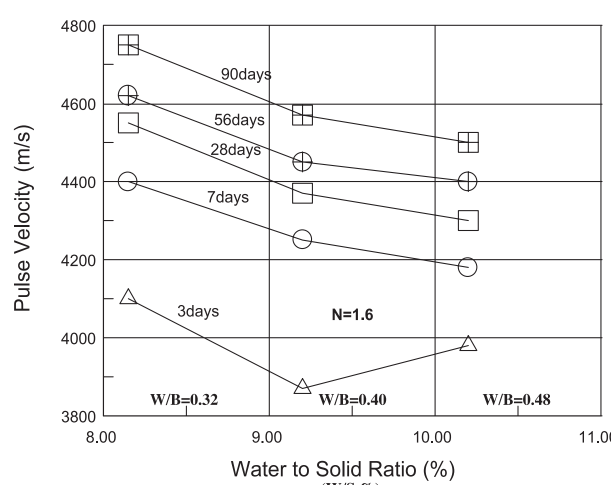


Fig. 6. The relationship between pulse velocity and W/S ratio at $N = 1.6$.

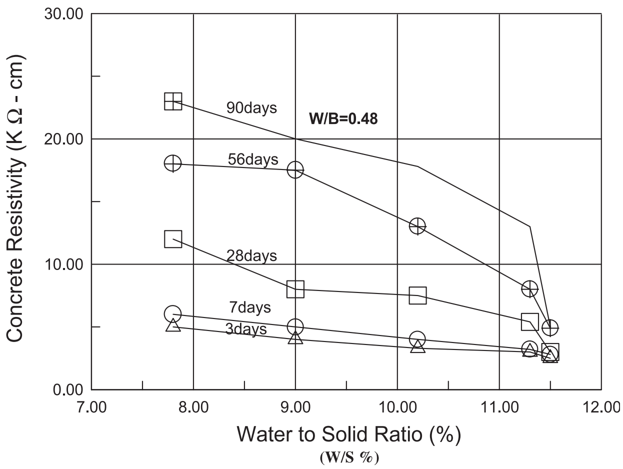


Fig. 7. The relationship between concrete resistivity and W/S ratio at W/B = 0.48.

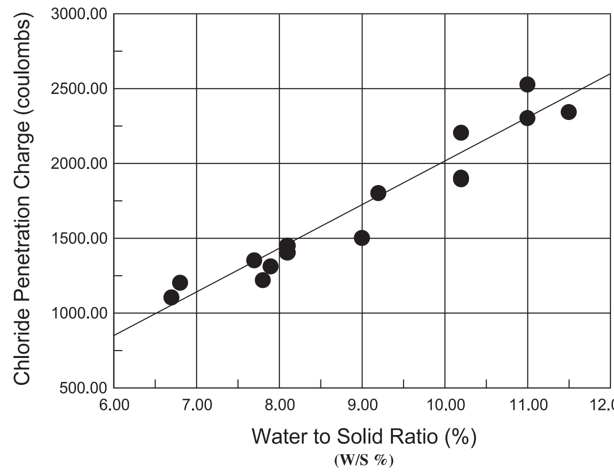


Fig. 9. The relationship between chloride penetration charge after 90 days and W/S ratio.

when $N$ equals 1.6, which appears to be inversely proportional to the W/S ratio.

### 5.4. Electrical resistivity

Concrete with lower conductivity provides higher protection against corrosion of steel. Fig. 7 shows the relationship between concrete resistivity and W/S ratio of different mixtures with W/B fixed at 0.48. It clearly indicates that electrical resistivity is inversely proportional to the W/S ratio. This may be due to the effect of the amount of water and pozzolanic materials used in the mixture on the microstructure of the concrete. The electrical resistivity of the traditional concrete is lower than 10 K Ω cm before the age of 90 days, causing problem of durability. Similarly, when $N$ equals 1.6, the change in the pulse velocity with respect to W/B ratio is also inversely proportional to the W/S ratio, as is illustrated in Fig. 8.

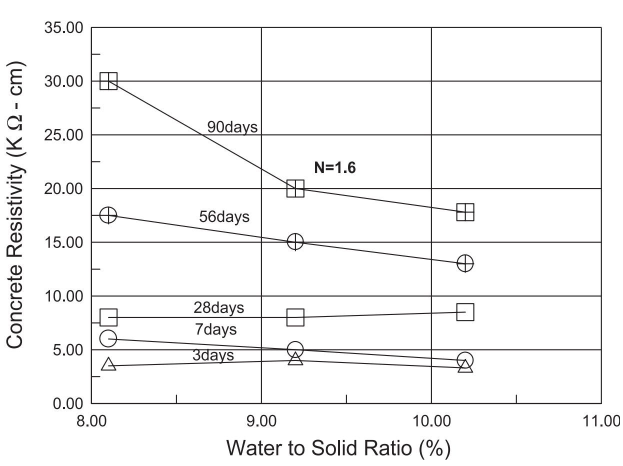


Fig. 8. The relationship between concrete resistivity and W/S ratio at $N$ = 1.6.

### 5.5. Chloride penetration

The penetration of chloride into the concrete can be determined by measuring the current passing through the concrete. Fig. 9 shows the relationship between penetrating current and W/S ratio after 90 days. Similar chloride penetration charge can be observed on HPC mixtures with W/B ratio ranging from 0.30 to 0.48 under the same W/S ratio. However, the penetrating current of the traditional concrete could reach as high as 21,600 C. Apparently, the durability may be quite a serious problem for concrete without the addition of pozzolanic materials. Although higher strength can be reached at an early age (e.g., 28 days), when the W/S ratio gets higher, lower resistivity and higher chloride penetration are the two factors creating the most disturbance to long-term durability.

## 6. Conclusions

The DMDA has proved to be capable of producing HPC with slumps of 230–270 mm and strength of $f'c$>56 MPa while avoiding water bleeding and segregation of aggregate. The use of domestic pozzolanic materials and strong water-reducing agent also contributes to the high strength and workability of concrete. For concrete pastes with the same W/C ratio, greater specific gravity will result in higher concrete strength. The lesser the cement is used, the higher the strength will be. The utilization of fly ash and slag is beneficial to the rheological properties of the HPC. The heat evolution curve of HPC produced with fly ash and slag is similar to that with cement paste, which varies depending mainly on the cement content. The results have shown that the utilization of fly ash and slag contributes to the development of long-term strength and durability of the HPC. With the proper amount of binder used, the mixture with W/B = 0.48 displays higher pulse velocity. Electrical resistivity and chloride penetration of HPC appear to be less sensitive to W/B ratio but are directly proportional to W/S ratio, supporting the argument that water content can have a significant effect on the durability of concrete.

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