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# Mix design of low-cement concrete with particle packing concept and superplasticizer application





## Abstract

The amount of cement paste used in concrete depends on aggregate particle packing, where the denser combination among particles with different particle sizes results in a minimum volume of voids (Vv). Theoretically, cement paste volume (Vp) is required to fill the void with the combination of fine and coarse aggregate, i.e., Vp/Vv = 100%. The purpose of this paper was to propose a concrete mix design method that could maximize the particle packing of aggregates to reduce the cement content in concrete mixture, hence producing low-cement concrete (LCC). The variables proposed were the ratio between the volume of paste to the volume of voids (Vp/Vv) as opposed to the cement content and the use of superplasticizer to control the workability of the fresh concrete. The results showed that by the combination of multi-sized coarse aggregates and fine aggregate, the smallest void volume of 23.5% could be achieved. The theoretically lowest cement content needed for a mixture with w/c 0.5 was 287 kg/m$^3$. However, after trial mixing, the cement requirement was found to be almost equal with conventional concrete, i.e., about 310 kg/m$^3$. Workability of the mixture depended on the paste volume

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# Implementation of a disaster management system for local governments in Japan

**T Goso[1], T Kakuzaki[2] and S Kusayanagi[3]**

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**Abstract.** Reconstruction after the Great East Japan Earthquake in March 2011 has been delayed. To suitably respond to similar large-scale disasters in the future, the implementation of a disaster management system at the local municipal level, aimed at rapid reconstruction that includes management of processes from pre-disaster to the reconstruction phase, is required. In this study, we develop a prototype of such a system, which is referred to as the Local Government Disaster Management System (LGDMS). For our study, we collaborate with a municipality in Kochi, Japan. In the LGDMS prototype, we use a Work Breakdown Structure (WBS) format, wherein the contents of each activity and roles of different organizations in those activities are defined based on a study of organizational problems and law and regulation issues among the central government, prefectural governments, and municipal governments. The Construction Management Committee of the Japan Society of Civil Engineers (JSCE) established a subcommittee for this research. This subcommittee is composed of university faculty members, local consulting engineers, and administrative officials in Tohoku and Kochi. The subcommittee is striving to implement LGDMS in several municipalities in Kochi.

## 1. Introduction

After the Great East Japan Earthquake in 2011(GEJE), disaster management including pre-disaster planning, rescue operations, recovery efforts, and reconstruction became a priority in Japan. Disaster management efforts focused specifically on municipal governments being at the forefront when any kind of disaster is occurring. Kakuzaki et al [1] summarized necessary activities and procedures of the activities for each aspect of disaster management. A management system which includes WBS (work breakdown structure), the contents of each activity, and work sequence to facilitate rapid and efficient recovery for any phase was developed in the research. It was named Disaster Management System. Researchers developed a prototype of the system for rural municipal governments in Japan, which they called the Local Government Disaster Management System, or LGDMS.

Any existing plans of rural municipal governments such as disaster prevention plans, debris disposal plans, temporary housing construction plans, evacuation plans, etc., successfully address damage predictions such as number of fatalities, number of collapsed buildings, amount of debris, etc. However,

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# A review: Adaptation of escape route for a framework of road disaster resilient

**A A Redzuan[1], A N Anuar[1], R Zakaria[2], E Aminudin[2,3*], N E Alias[1], M A M Yuzir[1] and M R Alzahari[2]**

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**Abstract.** Transportation system plays a vital role in sustaining the economic and social well-being of a community. Disaster or extreme hazard such as earthquake, storms, landslide, flood, terrorism, etc. has a major impact on the resilience of the road, especially in ensuring the impact toward the recovery for communities. Road infrastructure is linked to many encompassing factors such as road user, climate, economy, material, topography and periodic maintenance. Recently, unpredicted climate causes heavy rain, landslide, and flood resulting in high losses bared by the government on the repair and reconstruction works. Previous events have revealed that certain road areas in Malaysia are vulnerable after exposed to damage due to the natural disaster. This paper highlights the identified factors that contribute to adaptation on the escape route for road disaster resilient. A comprehensive review was done to identify a few missing approaches in the road network resiliency, which include a temporal route option as part of the adaptive routing solution. The research is expected to become a reference to overcome disruption in the road network in time of disaster or crisis while supporting the government initiative to strengthen the resilience of the nation’s infrastructure.

## 1. Introduction

Land transportation system plays a vital role in sustaining the economic and social well-being of communities. On occurrence of extreme hazard such as earthquake, storms, landslide, flood and terrorism, the condition of such networks have a significant impact on the recovery of the community. [1-6]. Human activities are highly depending on road as a medium for traveling. Road is defined as a route or open way from one place to another [7]. Technically, roads can be referred to land transportation infrastructure that serves as a platform for movement of motor, wheeled vehicles. In the research world, the resilience of roads to handle disaster are divided into three main areas; 1) road network design, 2) emergency traffic management, and 3) evacuation route [8].

According to the emergency database (EM-DAT) on statistics of disaster events around the world [9], frequency of disaster events has increased and reached its peak in 2000, and have more than 350 happened every year in the last decade. Disaster tremendously degrades social quality and does more damage in developing countries, which makes the effort to rescue and relief operations more significant.

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# Thermoelectric district supply concept including e-mobility

**A Mack[1], L Lackovic[1], W Lisin[1], C Blatt[1] and H Garrecht[1]**

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**Abstract.** The main objective of the environmental protection is the sustainable energy supply of residential areas. This is made possible by networking several buildings in the same district in order to produce a sustainable, efficient and self-sufficient supply of electrical and thermal energy. The second elementary topic is the conversion from combustion engines to electric mobility, i.e. from thermal to electrical energy. A novel concept of networking different storage facilities, energy producers and consumers will enable a sustainable, self-sufficient energy supply for districts. A special feature of this energy management design is networking of electrical and thermal systems with subsequent integration of electro-mobility into the districts plant system. Energy consumption and energy generation were simulated in an exemplary project of a district containing three new low-energy buildings. The results show that a self-sufficient supply of this district is possible with intelligent control of charging cycles and charging capacity and with the use of a new storage facility for electrical energy - a Compressed Air Energy Storage system. This model concept makes not only a considerable contribution to the electro-mobility conversion, but also enables an energy-efficient and sustainable electrical and thermal supply of the district.

## 1. Introduction

Sustainability and environmental protection are two elementary objectives of modern society. In order to achieve an energy-efficient and self-sufficient energy supply for districts, intensive networking of the individual buildings and control of the various components is implied. For this purpose, a concept based on networking and self-sufficiency was developed on the Institute for Materials in Civil Engineering at the University of Stuttgart. It combines thermal and electrical subsystems of plant engineering equipped with a Compressed-Air Energy Storage (CAES) technology. As the politics in the automotive industry currently show a descending trend toward the $CO_2$ emission reduction, a further goal would be therefore to switch to integrated electro-mobility concept in the residential sector. This is only efficient and sustainable if the required power would be generated from renewable sources. The present concept integrates electro-mobility into the system scheme and serves as a modular, universally applicable approach for the energetic supply to district typologies of different sizes. It is based on intelligent planning through simulation, networking and control of different generators, storage facilities and consumers.

The developed district networking concept is based on an intelligent distribution and the temporal shift of the generated power by means of electrical and thermal storage. It is designed under three main assumptions: (I) the parking spaces in the district are designed as electric vehicle (EV) parking spaces, (II) the self-sufficient energy supply of these parking spaces is made possible through electrical energy

# Effects of w/b ratio, fly ash, and chloride content on corrosion of reinforcing steel

**D T V Phuong[1], P Sancharoen[2*], P Klomjit[3] and S Tangtermsirikul[1]**

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**Abstract.** To predict the corrosion of reinforcing steel, the electrochemical properties of reinforcing steel with different concrete mix proportions and chloride content were studied. The water to binder ratio of concrete was varied (0.45 and 0.60). Coal fly ash was used to replace OPC (0 and 30% by weight of the total binder). The initial chloride was 0, 2, and 4% by weight of concrete. Potentiodynamic polarization testing was conducted by controlling the moisture of specimens. The Tafel slope, corrosion potential, and corrosion rate were analyzed from the testing results. Results show that chloride content significantly affects the electrochemical properties of reinforcing steel. The anodic Tafel slope decreased as chloride content increased. The cathodic Tafel slope increased when the water to binder ratio decreased, or when the fly ash content increased due to a denser concrete pore structure, limiting oxygen diffusion. Results from this study can be used to simulate the corrosion of reinforcing steel and predict the service life of reinforced concrete structures. Also, the electrochemical compatibility between existing and repaired sections can be evaluated to ensure the durability of repaired RC structures.

## 1. Introduction

The corrosion of reinforcing steel (RC) is a major problem, deteriorating reinforced concrete structures worldwide. To ensure the safety of an RC structure throughout its service life, performance prediction must be accurately performed. For the corrosion of reinforcing steel, the deterioration mechanism is normally classified into 4 stages: corrosion initiation, corrosion propagation, corrosion acceleration, and deterioration. In each stage, different prediction models are required. For example, corrosion initiation due to chloride attack or carbonation can be predicted based on Fick's 2$^{nd}$ diffusion law. After corrosion has been initiated, the time to corrosion cracking can be predicted based on the corrosion rate of reinforcing steel and structural conditions such as concrete strength or the location of the reinforcing steel. Many researchers studied the corrosion rate of reinforcing steel [1]. It is well known that the corrosion rate depends on concrete properties such as chloride content, pH, moisture, oxygen, temperature, electrical resistivity, etc. In previous studies, the corrosion rate was measured by corrosion mass loss, embedded corrosion sensors, linear polarization, half-cell potential, or electrical resistivity. Equations to predict the corrosion rate has been proposed.

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# Mix design of low-cement concrete with particle packing concept and superplasticizer application

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# Mix design of low-cement concrete with particle packing concept and superplasticizer application

**Penulis 1, Penulis 2, penulis 3 dan Penulis 4**

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**Abstract.** The amount of cement paste used in concrete depends on aggregate particle packing, where the denser combination among particles with different particle sizes results in a minimum volume of voids (Vv). Theoretically, cement paste volume (Vp) is required to fill the void with the combination of fine and coarse aggregate, i.e., Vp/Vv = 100%. The purpose of this paper was to propose a concrete mix design method that could maximize the particle packing of aggregates to reduce the cement content in concrete mixture, hence producing low-cement concrete (LCC). The variables proposed were the ratio between the volume of paste to the volume of voids (Vp/Vv) as opposed to the cement content and the use of superplasticizer to control the workability of the fresh concrete. The results showed that by the combination of multi-sized coarse aggregates and fine aggregate, the smallest void volume of 23.5% could be achieved. The theoretically lowest cement content needed for a mixture with w/c 0.5 was 287 kg/m³. However, after trial mixing, the cement requirement was found to be almost equal with conventional concrete, i.e., about 310 kg/m³. Workability of the mixture depended on the paste volume to void volume ratio (Vp/Vv > 100%) and was greatly influenced by the superplasticizer content. The use of excessive superplasticizer could cause bleeding due to lack of fine particles in the low cement concrete mixture. The use of cementitious material, such as fly ash by 50%, to replace cement, significantly improves the workability and reduces the cement content below the minimum cement requirement with similar compressive strength as the water to cementitious ratio mainly controls compressive strength.

## 1. Introduction

Concrete with a high proportion of cement is not only expensive but also causes a high risk of cracking due to shrinkage [1]. In concrete, there are empty voids between the coarse and fine aggregates that should be filled by a paste consisting of cement and water. Particle packing is one of the methods used to reduce the use of cement in concrete. Particle packing mix design methods aim to combine aggregates of different sizes to achieve the densest possible condition by making the voids as small as possible [2]. This reduces the amount of cement paste needed and, therefore, the amount of water required, thus increasing the strength [3, 4].

Conventionally, concrete has a minimum cement content requirement based on the maximum aggregate size used [5]. This requirement applies to concrete mixtures without the use of admixture chemicals. Reducing the proportion of cement in concrete is very important because cement replacement by cementitious materials, such as fly ash, can be utilized [6]. According to Lamond and Pielert [7], reducing the proportion of cement in a concrete mixture causes the concrete to become stiff and unworkable. Therefore, the proportion of other materials, such as fine and coarse aggregates, must be considered carefully in order to avoid these risks.

Low-cement concrete (LCC) is an environmentally friendly concrete that uses a small amount of cement. With a low proportion of cement, the risk of cracking in the concrete will be reduced due to the reduced autogenous shrinkage potential [1, 8]. Low cement content also reduces the cost of the concrete. However, there is a problem of workability with the reduction of fine particles volume in concrete mixture. As the cohesion of the matrix can be reduced, the use of admixture chemicals, such as superplasticizers, may not help improve the workability of concrete with low cement content [9].

In this study, we investigate a simplified mix design method by analyzing the void volume (Vv) on coarse aggregates of different sizes combined with sand as fine aggregate as the basis for particle packing concept. The paste content (Vp) is calculated as the theoretical paste volume of the combination of water and cement for specific water to cement ratio. Controlling the workability of the mixture was done by adjusting the ratio of paste volume to the void volume (Vp/Vv) and the addition of superplasticizer. Furthermore, the application of fly ash as cementitious material reducing the use of cement was shown as a beneficial addition in improving the workability and strength of the concrete mixture.

## 2. Procedures of low-cement concrete mix design

Coarse aggregate of various sizes and fine aggregate that is going to be used in the concrete should be obtained for the measurement of void volume. The specific gravity of the aggregate needs to be tested for the material combination. The void volume of the aggregate is calculated as the fraction of void in aggregate by filling the aggregate in a steel container with known volume and use a vibrating machine to compact the aggregate. A combination of testing was carried out to determine the composition of sand and coarse aggregates as densely as possible based on the void volume. The equipment prepared is a cylindrical volume tub with diameter of 10 cm and a height of 15 cm and a vibrating machine. Fine and coarse aggregates used are in saturated-surface-dry (SSD) conditions. Void volume in percentage is calculated as the ratio of bulk density to its specific gravity (GS). When there is a combination of two sizes of aggregate, the specific gravity is calculated by equation (1):

$$\text{Void Volume (\%)} = \frac{\text{Total bulk density}}{A(GS_1) + B(GS_2)}, \tag{1}$$

where $GS_1$ is the specific gravity of aggregate 1, $GS_2$ is the specific gravity of aggregate 2, A and B are the mass fraction ratios of the aggregate, total bulk density is the measured bulk density from the compaction test in kg/m$^3$, and the void volume is the measured void volume fraction of the combined aggregate.

Minimum cement content is calculated in equation (2) as the theoretical minimum cement content from the void volume measurement and the water to cement ratio (w/c) so it can fill all the void volume in the aggregate:

$$\text{Minimum cement content (kg/m}^3\text{)} = \frac{\text{Void Volume(\%)} \times 1000}{w/c + \dfrac{1}{GS_{\text{cement}}}} \tag{2}$$

The minimum cement content required is dependent on the selection of water to cement ratio and the void volume from the combination of the aggregates. Figure 1 shows the minimum cement content needed to fill the void volume in relationship to the w/c. Higher void volume requires higher cement content, whereas increasing the water to cement ratio reduces the cement content needed in the mixture. After calculation of the required cement content, the mixture composition of the concrete can be calculated. The cement content calculated here is measured as the paste volume to void volume ratio (Vp/Vv) at 100%, with the implication of the paste volume would fill all voids in the aggregate. This condition is not necessarily the ideal condition because a minimum paste volume in concrete mixture would cause a harsh mixture and very low workability. The Vp/Vv ratio should be increased to more than 100% to produce a more workable mixture. The superplasticizer dosage needs to be adjusted during the trial mix to obtain a cohesive and workable mixture.

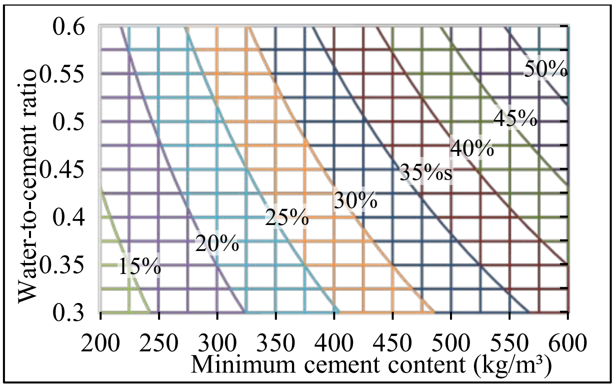


**Figure 1.** Theoretical minimum cement content and the water to cement ratio needed to fill the volume of voids in aggregate.

## 3. Materials and methods

The research aims to analyze the amount of cement paste based on void volume values in the densest aggregate combination and using a superplasticizer to improve the workability of concrete. This study also analyzes the effect of adding paste amount on concrete workability and the effect of maximum aggregate size on the amount of cement needed.

### *3.1. Materials*

The material used to make concrete was river sand as the fine aggregate, crushed stone as the coarse aggregate, cement and fly ash as cement replacement, superplasticizers, and water. The coarse aggregates used were crushed stone of various sizes (4.75–25 mm). The fine aggregate was river sand from Lumajang, East Java, Indonesia. The cement used was Portland Pozzolan cement (PPC) from Gresik Cement. The fly ash used was class C fly ash from Paiton power plant in East Java, Indonesia, which had been studied previously [10, 11]. The superplasticizer used was polycarboxylate-based MasterGlenium SKY 8851 from BASF.

### *3.2. Methods*

The mix design process began by analyzing the void volume in various combinations of coarse aggregates and fine aggregates. Void volume analysis was started by using coarse aggregate of single size (25 mm, 15 mm, 12.5 mm, and 8 mm) combined with fine aggregate. The void volume analysis was also carried out by using multi-sized coarse aggregates (25–12.5 mm and 12.5–4.75 mm) combined with the sand. After analyzing the void volumes of various combinations, an analysis of the cement requirements according to the theoretically obtained void volume was performed.

Mix design of the concrete in this study was divided into three parts. The first part investigated variation of the water to cement ratio (w/c), with w/c of 0.3, 0.35, 0.4, and 0.5 by analyzing the actual use of the cement content and the needs of superplasticizer (T series). The second part of the mix design was casting concrete using a combination of two sizes of coarse aggregate with varying ratios of Vp/Vv (A and B series) at a w/c of 0.35. The second part aimed to determine the effect of increasing Vp/Vv on the workability of concrete with the application of superplasticizer to control the workability. The third part of mix design was replacing part of the cement with fly ash to reduce cement usage to investigate the effect of cementitious materials and Vp/Vv to the workability of concrete with the application of superplasticizer to control the mixture's workability (C series).

## 4. Results and discussion

### *4.1. Low-cement concrete mix proportion*

*4.1.1. Aggregate combination and minimum void volume.* Void volume analysis was carried out to find out the voids contained in the combination of coarse and fine aggregates. The voids contained in combination of coarse and fine aggregates are then filled with cement paste. Void volume analysis was performed with combinations of coarse aggregates of various maximum sizes and sand as the fine aggregate. The aggregates were put in in a cylindrical steel container and then vibrated for 10 seconds until the container was filled and packed down. An average of the two measurements was obtained for each variation.

The first void volume test used coarse aggregates of 25 mm, 15 mm, 12.5 mm, and 8 mm, each combined with the fine aggregate. The second test was done on the sand with coarse aggregate, combining the 25 mm and 12.5 mm sizes, and the third combination was sand and coarse aggregate, combining the 12.5 mm and 4.75 mm sizes. Each combination was done at 100% coarse aggregate, 80% coarse aggregate and 20% sand, 60% coarse aggregate and 40% sand, 40% coarse aggregate and 60% sand, 20% coarse aggregate and 80% sand, and 100% sand.

Figure 2 compares the void volume values of different maximum aggregate sizes with the percentage combination of coarse and fine aggregates. The results obtained using a single size coarse aggregate show that the larger the maximum coarse aggregate used would result in a lower void volume. The densest conditions were reached on average at 60% coarse aggregate and 40% fine aggregate by volume. However, by using a combination of coarse aggregates of 25 mm and 12.5 mm, a lower void volume can be obtained that only uses a single size aggregate of 25 mm. The lowest void volume obtained was 23.5% void volume by a combination of 45% coarse aggregate and 55% sand. Similarly, the combination of coarse aggregate sizes of 12.5 mm and 4.75 mm produced a smaller void volume compared with using only a coarse aggregate size of 12.5 mm. The lowest void volume at 27.5% was obtained at 50% of fine and coarse aggregate.

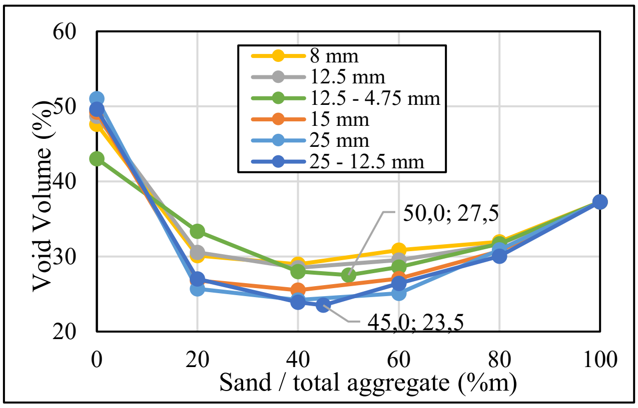


**Figure 2.** Combination of fine and coarse aggregates to achieve the lowest void volume.

These results are in line with previous studies [12] where the densest conditions were achieved in combination with 60% coarse aggregate mass and fine aggregate mass of 40% for coarse aggregates of size 6–16 mm and fine aggregates measuring 0–4 mm. Using a packing particle simulation program, maximum density obtained could reach up to 84%, which means only a 16% void volume. Results were obtained from the combination of 35% fine aggregate size 0–4 mm, 25% coarse aggregate measuring 6–16 mm, and 40% coarse aggregate with sizes 16–32 mm. Many factors influence the highest packing particles such as the particle shape, aggregate size and gradation, and the compaction method.

*4.1.2. Paste content in the concrete mixture.* With the particle packing method applied, an analysis of the amount of cement needed against the void ratio was carried out to determine the amount of cement needed theoretically to make concrete using a combination of coarse and fine aggregates that yielded the smallest void volume. The amount of cement needed is also influenced by the water to cement ratio (w/c) determined in the mix design to obtain the desired compressive strength. The amount of cement needed based on void ratios was obtained from various theoretically different maximum aggregate sizes as displayed in figure 3. The minimum cement demand is results from using coarse aggregates measuring 25–12.5 mm, that is, with cement requirements of 287 kg/m³ at w/c of 0.5. This cement requirement is quite low compared with the minimum cement content requirements according to ACI Committee 302 [5], which is 310 kg/m³ for aggregates with a maximum size of 25 mm. However, the cement demand is only theoretically obtained at a fairly high w/c so that it will reduce the compressive strength of the concrete due to the increase of porosity. For w/c of 0.4, 0.35, and 0.3, the need for cement is still not low because it still exceeds the minimum cement requirement.

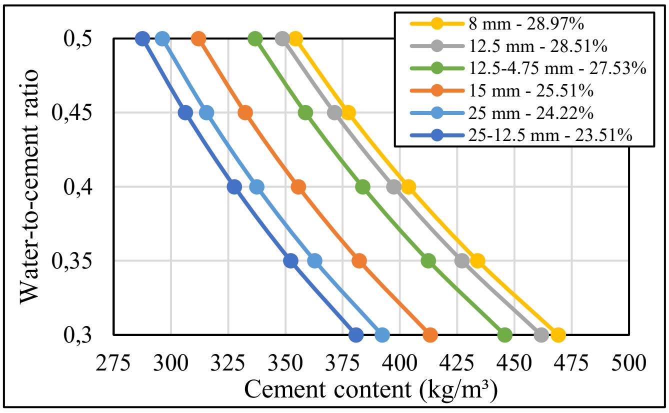


**Figure 3.** Cement content and water to cement ratio needed to fill the volume of voids for different combinations of aggregate size and gradation.

During the trial mix, the paste content and superplasticizer dosage were controlled so that the fresh concrete could be mixed thoroughly and without bleeding and segregation. When making concrete with w/c of 0.5, the use of paste volume at Vp/Vv of 100% had not shown a good result. This was possibly due to the lack of water in the fresh concrete mixture. By adding water, the quality of the concrete was reduced so that a superplasticizer of 0.2% by mass of cement was added. However, bleeding and segregation still occurred and the fresh concrete was still unworkable (figure 4). The addition of a large amount of superplasticizer directly in the mixture caused excessive bleeding. With the gradual addition of superplasticizers, the risk of bleeding in fresh concrete can be minimized. To obtain a workable concrete mixture, the paste volume to void volume ratio (Vp/Vv) was increased about 10% so that the majority of the concrete mixture used had Vp/Vv of 110%. The fresh concrete produced was shown to be cohesive although the slump value was still low. Obla [13] stated that a reasonable paste volume should be around 25% to 30% for a workable mixture, which converts the Vp/Vv of regular concrete to around 110–120%.

From the trial mix results, a higher value of Vp/Vv improved the workability of fresh concrete. The cement content in the mixture needs to be changed with higher Vp/Vv. At w/c of 0.4, 0.35, and 0.3, the superplasticizer and the paste volume was increased gradually until the fresh concrete mixed cohesively. The actual mix design results with different Vp/Vv are reported in table 1. A series of four concrete mixtures was investigated to observe the effect of variation of w/c, a combination of larger and smaller-coarse aggregate, and the utilization of cementitious materials in the mixture. The fresh and hardened properties of the concrete produced are shown in table 2.

**Figure 4.** Segregated concrete with w/c of 0.5, Vp/Vv of 100%, and superplasticizer dosage of 0.2% by mass of cement.

**Table 1.** Mix designs of the produced concrete.

| Code | Coarse Agg. Size (mm) | w/c | Cement (kg/m$^3$) | Fly Ash (kg/m$^3$) | Water (kg/m$^3$) | Fine Agg. (kg/m$^3$) | Coarse Agg. (kg/m$^3$) | Vp/Vv (%v) |
|---|---|---|---|---|---|---|---|---|
| T1 | | 0.5 | 309 | - | 154 | 928 | 1101 | 110 |
| T2 | 25 – 12.5 | 0.4 | 328 | - | 131 | 950 | 1127 | 100 |
| T3 | | 0.35 | 385 | - | 135 | 923 | 1095 | 112.5 |
| T4 | | 0.3 | 409 | - | 123 | 928 | 1101 | 110 |
| A1 | | 0.35 | 402 | - | 141 | 909 | 1079 | 119 |
| A2 | 25 – 12.5 | 0.35 | 416 | - | 145 | 897 | 1064 | 125 |
| A3 | | 0.35 | 429 | - | 150 | 885 | 1050 | 131 |
| B1 | | 0.35 | 418 | - | 146 | 995 | 916 | 102 |
| B2 | 12.5 – 4.75 | 0.35 | 432 | - | 151 | 981 | 904 | 107 |
| B3 | | 0.35 | 445 | - | 156 | 968 | 892 | 112 |
| C1 | | 0.35 | 198 | 198 | 139 | 897 | 1064 | 125 |
| C2 | 25 – 12.5 | 0.35 | 205 | 205 | 144 | 887 | 1052 | 130 |
| C3 | | 0.35 | 212 | 212 | 148 | 876 | 1039 | 136 |

**Table 2.** Fresh and hardened properties of the produced concrete.

| Code | w/b | Cementitious material (kg/m$^3$) | Vp/Vv (%v) | SP added (%m of cm) | Slump (cm) | Concrete Density (kg/m$^3$) | 28 days' Compressive Strength (MPa) |
|---|---|---|---|---|---|---|---|
| T1 | 0.5 | 309 | 110 | 0 | 1 | 2477 | 15.30 |
| T2 | 0.4 | 328 | 100 | 0.066 | 2.5 | 2482 | 22.64 |
| T3 | 0.35 | 385 | 112.5 | 0.253 | 4 | 2505 | 28.86 |
| T4 | 0.3 | 409 | 110 | 0.328 | 0 | 2544 | 41.00 |
| A1 | 0.35 | 402 | 119 | 0.158 | 2 | 2488 | 35.60 |
| A2 | 0.35 | 416 | 125 | 0.203 | 3.5 | 2506 | 36.78 |
| A3 | 0.35 | 429 | 131 | 0.210 | 4.5 | 2516 | 40.74 |
| B1 | 0.35 | 418 | 102 | 0.197 | 0 | 2454 | 49.51 |
| B2 | 0.35 | 432 | 107 | 0.200 | 1 | 2463 | 37.63 |
| B3 | 0.35 | 445 | 112 | 0.203 | 4 | 2472 | 41.31 |
| C1 | 0.35 | 396 | 125 | 0.207 | 17.5 | 2490 | 44.14 |
| C2 | 0.35 | 410 | 130 | 0.162 | 19 | 2499 | 41.88 |
| C3 | 0.35 | 424 | 136 | 0.054 | 16 | 2503 | 33.95 |

### *4.2. Fresh concrete behavior of low-cement concrete*

Workability of the fresh concrete is characterized by the slump values shown in figure 5. Concrete of the T series was shown to have no trend due to different paste viscosity with the increase of w/c. For the concrete with different maximum aggregate size, the workability of concrete with a smaller maximum aggregate size of 12.5–4.75 mm (B series) was lower even though it uses higher cement content compared with cement used for concrete with a coarse aggregate size of 25–12.5 mm (A series). This can be explained by the lower Vp/Vv value of the B series because the void volume was higher at the combination of 12.5–4.75 mm aggregates.

It also needs to be noted that the superplasticizer dosage was increased with the increase of Vp/Vv used for the A and B series. The superplasticizer was added gradually when mixing the concrete and the higher paste volume required a higher dosage for a cohesive mixture.

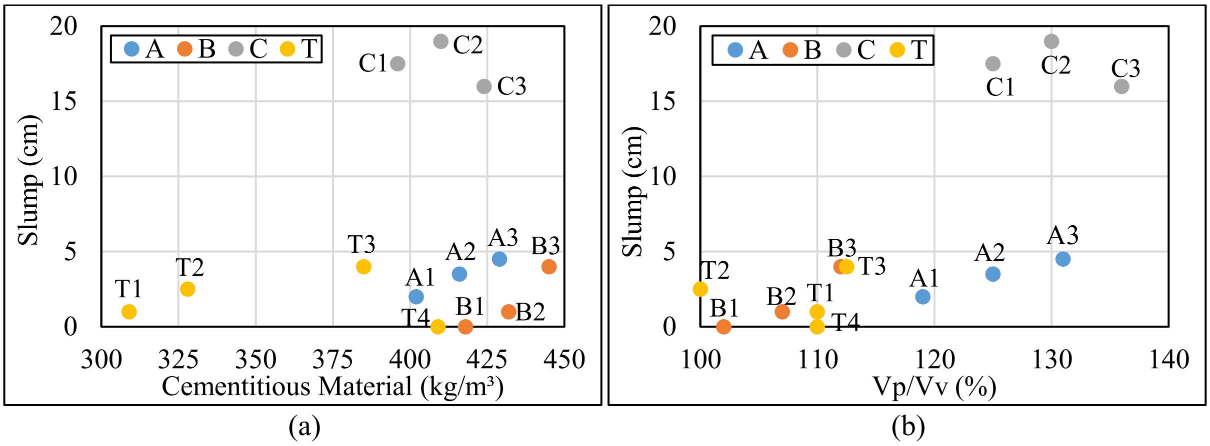


**Figure 5.** Relationship of the slump value of the fresh concrete based on (a) the cementitious materials content and (b) paste volume to void volume ratio (Vp/Vv).

Different behavior was observed on concrete that utilized fly ash as a partial cement replacement (C series). The fly ash was substituting as much as 50% of the cement, by mass, to produce excellent workability. The use of superplasticizer decreases with the increase of Vp/Vv. The spherical particle shape of the fly ash mainly contributes to an increase of workability and reduces the water and superplasticizer demand in the concrete. Concretes of the C series had more than 15 cm of the slump value. The ratio of paste volume to void volume (Vp/Vv) also increases by replacing 50% cement with fly ash because the specific gravity of the fly ash is lower than that of cement. Thus, for concrete with fly ash as the cementitious materials, lower Vp/Vv can be utilized.

### *4.3. Concrete compressive strength*

The concrete compressive strength test was carried out at 28 days with two replications for each mix design. The concrete sample was cured in water until one day before the testing. Sulfur capping was used to ensure a flat testing surface. The compressive strength of the T series to show the variation of w/c is shown in figure 6. The compressive strength was increased with reduced w/c consistent to the common knowledge in concrete technology. However, the compressive strength obtained was relatively low at the same w/c compared with the reference [14]. The lower strength can be attributed to the lower workability of the concrete due to the reduced paste volume.

Figure 7 shows the compressive strength of the concrete produced at w/c of 0.35. The figure shows that for the A series, the higher amount of cement and Vp/Vv the higher the compressive strength obtained. However, the same condition was not observed for the B series. Although the Vp/Vv of the B series was lower, higher compressive strength was obtained, indicating other factors influencing the strength. Smaller maximum aggregate size typically produces concrete with higher strength due to the reduced microcracks in the aggregate itself. These results are the same as those obtained by Gillespie et al. [15], where the larger the maximum aggregate size, the lower the strength of the concrete. This shows that the addition of cementitious material and an increase of Vp/Vv do not necessarily produce higher compressive strength.

When replacing the cement with 50% fly ash, by mass, in the C series, the compressive strength of the concrete obtained was similar to the A series although the cement content was half of the A series. The highest compressive strength produced was 44.14 MPa with w/c of 0.35 and the use of cement and fly ash for both was 198 kg/m³. This strength was higher than the one obtained in the A series, which was 40.74 MPa with cement content of 429 kg/m³. This result suggests that for increased strength and workability, good quality cementitious material such as fly ash needs to be used as an additional material in the mixture. With the use of fly ash, the cement content actually can be lowered much more compared with the minimum cement content required by the ACI 302 [5].

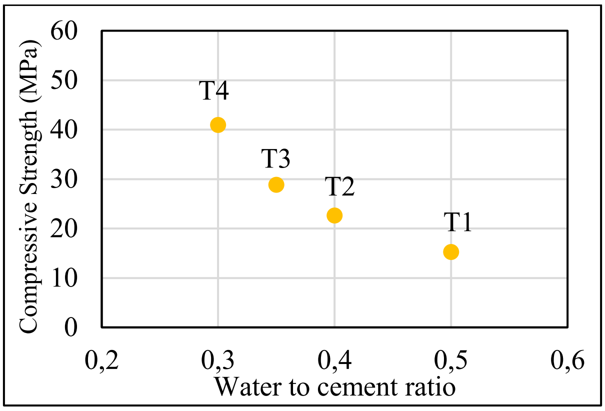


**Figure 6.** Compressive strength of the T series concretes with varied water to cement ratio.

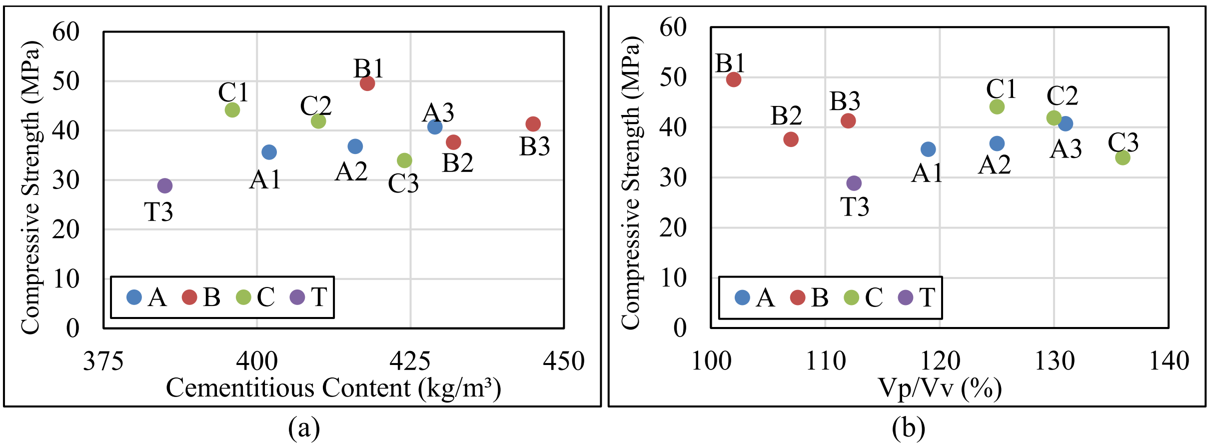


**Figure 7.** Relationship of 28-day compressive strength of the concrete with w/cm of 0.35 to (a) the cementitious materials content and (b) paste volume to void volume ratio (Vp/Vv).

## 5. Conclusions

The following conclusions can be drawn from the study results:

- With the smallest void volume of the aggregate combination (23.5%), the required theoretical cement demand is 287 kg/m³ with water to cement ratio (w/c) of 0.5. After trial casting, the cement demand increases to reach 309 kg/m³ (similar to the ACI 302 at 310 kg/m³). Compressive strength is still relatively low due to low workability, but can be increased by lowering the water to cement ratio.

- Usually, the cement content needs to be increased, at constant water content in concrete mixture, in order to increase the compressive strength of concrete by reducing the w/c. However, when considering the constant paste volume to void volume ratio (Vp/Vv), the water content should be reduced and the cement content needs to be increased when higher concrete strength is required.
- The replacement of cement with 50% fly ash reduces cement usage to below the minimum cement requirement standard of ACI 302. Furthermore, the quality of the concrete is higher (44.14 MPa) than that of concrete using only cement (40.74 MPa).
- Adding superplasticizer to concrete with low cement content (287 kg/m$^3$) does not assist in improving workability and causes bleeding. Increasing Vp/Vv improves the workability of the fresh concrete mixture.

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