Mix design and properties of reactive powder concrete with diatomaceous earth as cement replacement

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Abstract. Reactive powder concrete (RPC) consuming a large amount of Portland cement results in high cost. To reduce the cement used in RPC, the silica fume and ground granulated blast-furnace slag have been used as cement replacement. However, those materials are not available in Aceh Province – Indonesia. The objective of this research is to propose the mix design of RPC composed of locally available materials. In this paper, the mix design of RPC using calcined diatomaceous earth powder as partial cement replacement is presented. The iron ore powder was used as filler, and river sand with a diameter of less than 1 mm was used as aggregate. To maintain the workability of concrete, superplasticizer was added. The bulk density, specific gravity as well as particle size distribution of Portland cement, diatomaceous earth powder, iron ore powder and river size were tested. The modified Andreasen and Andersen model was utilized. The mix proportion of materials was determined using an optimization algorithm based on the least-squares method. Furthermore, all materials were mixed to produce RPC; and then the properties of fresh and hardened concrete i.e. workability, air content, compressive strength, splitting tensile strength, and flexural strength, were tested. The relative slump flow decreases with the increase of diatomaceous earth binder. The RPC with diatomaceous earth powder has a lower 7 days compressive strength but high flexural strength and splitting tensile strength.

1. Introduction

Many studies have been done on using the geopolymer as the cement replacement in concrete production [1-4]. Reactive powder concrete (RPC) was introduced by Richard and Cheyrezy in 1990 and published firstly in 1995 [5]. Since then, many studies have been done [e.g. 6-10]. RPC composed of fine materials such as micro sand as aggregate and a large amount of Portland cement results in high cost. For example, Rossi [11] in his experimental work to study the mechanical behavior of RPC, used 1050 kg/m³ cement. Park et al. [12] used about 1000 kg/m³ cement in studying the effect of hybrid fibers on the tensile strength of RPC. Considering the high cost of RPC, the silica fume and ground granulated blast-furnace slag (GGBS) have been used as partial cement replacement. For example, Hasan et al. [13] used about 650 kg/m³ cement, 420 kg/m³ GGBS and 120 kg/m³ silica fume. El-Dieb [14] used about 900 kg/m³ cement and 135 kg/m³ silica fume. Tayeh et al. [15] used about 770 kg/m³ cement and 200 kg/m³ silica fume. Yu et al. [16] used about 875 kg/m³ cement and 44 kg/m³ micro-silica. However, silica fume and GGBS are not available in Aceh Province–Indonesia and it is very expensive for someone to order them from the other places. Based on this background, it is essential to find local material that can be used as the cement replacement. In this study, the calcined diatomaceous earth powder is used as partial cement replacement. The river sand with a diameter of less than 1 mm is used as aggregate. The iron ore powder,
which is the locally available material, is used as filler. Because of the different properties of the composed materials, it is important to determine the proportion of each material in RPC.

The purpose of this study is to propose the mix design of RPC composed of local materials. The mix proportion of materials was determined based on the modified Andreasen and Andersen model proposed by Funk and Dinger [17] to have the good packing density of the materials. The proportions of each material in the mixture are adjusted until an optimum fit between the composed mix, and the target curve is reached. The optimization algorithm based on the least-squares method was utilized.

2. Methodology

Several mix design tools have been proposed to design the mix proportion of concrete. De Larran and Sedran [18,19] postulated different approaches to design the concrete based on the properties of multimodal, discretely sized particles: the Linear Packing Density Model (LPDM), Solid Suspension Model (SSM) and Compressive Packing Model (CPM). Fennis et al. [20] later developed a concrete mix design based on the concepts of De Larrand and Sedran. However, all these design methods are based on the packing fraction of individual components and their combinations, and therefore it is complicated to include very fine particles in these mix design tools.

Based on the work of Fuller and Thompson [21], Andreasen and Andersen [22] developed a model in which a minimal porosity can be achieved by an optimal particle size distribution of all materials composing the concrete, as shown in the following equation:

\[
P(D) = (D/D_{\text{max}})^q \tag{1}
\]

where \( P(D) \) = a fraction of the total materials with particle size is smaller than \( D \), \( D = \) the particle size (\( \mu m \)), \( D_{\text{max}} = \) the maximum particle size (\( \mu m \)), and \( q = \) the distribution modulus.

Funk and Dinger [17] later modified the Andreasen and Andersen Model by taking into account the minimum particle size as follows:

\[
P(D) = [D^q - (D_{\text{min}})^q] / [(D_{\text{max}})^q - (D_{\text{min}})^q] \tag{2}
\]

where \( D_{\text{min}} = \) the minimum particle size. The value of \( q \) determines the proportion between the fine and the coarse particles in the concrete mixture. Higher value (\( q > 0.5 \)) leads to coarse mixture while lower value (\( q < 0.25 \)) leads to fine mixture.

The so-called Modified Andreasen and Andersen Model in Eq. (2) has been successfully utilized in optimization algorithms for the mix design of normal concrete [23,24], lightweight concrete [25,26] and ultra-high-performance fiber reinforced concrete [16].

The materials used in this study were Portland cement, diatomaceous earth powder, iron ore powder, river sand, superplasticizer, and water. The Portland cement produced by PT Semen Andalas Indonesia of Lhoknga – Aceh Besar District was used. The specific gravity of the cement is 3.15. The particle size distribution of the cement was tested using the particle size analyzer (PSA).

The diatomaceous earth was collected from Beureunuet Village – Aceh Besar District in the form of the chunk. The chunk of diatomaceous earth was burned in the brick-burning furnace for 4 days, then ground using the Los Angeles machine and sieved to form the powder having the particle sizes less than 250 \( \mu m \). The powder was then sieved to form the binder having the particle sizes less than 250 \( \mu m \). The binder was calcined at the temperature of 600 \( ^\circ C \) for 5 hours. On the calcined diatomaceous earth powder, the bulk density, specific gravity, and particle size distribution tests were performed. The calcined diatomaceous powder is used as the pozzolanic material for cement replacement.

The iron ore was collected from Leupung – Aceh Besar District. Same as diatomaceous earth, the iron ore then ground using the Los Angeles machine and sieved to form the powder having the particle sizes less than 250 \( \mu m \). The bulk density, specific gravity, and particle size distribution of the iron ore powder tests were then conducted. In this study, the iron ore powder is used as the filler.

The river sand was used as aggregate. The sand was sieved to have the particle sizes less than 1 mm. The bulk density, specific gravity, and particle size distribution tests were then performed. A
polycarboxylic ether-based superplasticizer from PT Sika Indonesia was used to adjust the workability of RPC. The specific gravity of the superplasticizer is 1.06.

Based on the properties and particle sizes distribution of composed materials, the mix proportion of RPC was designed. The Modified Andreasen and Andersen Model was adopted. The Modified Andreasen and Andersen Model (Eq. 2) acts as a target function for the optimization of the proportion of the materials. The value of 0.31 for q was used. The proportion of the materials was determined by trial and error until the deviation between the target curve and composed particle size distribution of the mixture is minimum. A least square method expressed by minimizing the sum of the square of the residuals is adopted.

Three mix proportions of RPC, which are the different content of diatomaceous earth binder, were designed. The diatomaceous earth binder was used to replace 0%, 5%, and 10% of cement weight. The mix proportion of RPC with no diatomaceous binder (mix #1) was first designed. The water to cement ratio of 0.2 was used. After all the material proportion is determined, on the mix #2 and mix #3, the weight of cement was replaced by 5% and 10% of diatomaceous earth binder.

After the mix proportions were determined, the mixtures were mixed in a concrete mixer. First, cement, diatomaceous earth binder, iron ore binder, and sand were mixed with slow speed for 30 seconds. Then, 80% of mixing water was added, mixed with slow speed for 90 seconds, and stopped for 30 seconds. Later, the remaining water and superplasticizer were added and mixed with slow speed for 180 seconds following by high speed for 120 seconds. This mixing procedure was adopted from Yu et al. [16].

The workability of fresh RPC was determined by the flow table test. The concrete mixture was filled on the cone. Once the cone was rose up, the mixture was flown around. Two diameters perpendicular to each other (d₁ and d₂) were measured. The relative slump (ξ) is calculated as follows:

$$\xi = \left[ \frac{(d_1 + d_2)}{2 \ d_o} \right]^2 - 1$$

where \(d_o\) is the based inner diameter of the cone.

The air content of fresh RPC was determined as follows. The concrete mixture was filled in the cylindrical container with a known volume and vibrated for 30 seconds. The weight of the concrete mixture was measured. By known the composition ratio of composed materials in the mix, then the weight of each material can be calculated. The weight of each material then converted to its volume by dividing the weight with the density. The air content (ϕ) therefore, can be calculated as follows:

$$\varphi = \frac{[(V_c - V_{pc} - V_{de} - V_{as} - V_s - V_w - V_{sp})/V_c] \times 100\%}{100\%}$$

where \(V_c\) = volume of the container, \(V_{pc}\) = volume of Portland cement, \(V_{de}\) = volume of diatomaceous earth binder, \(V_{as}\) = volume of iron ore binder, \(V_s\) = volume of sand, \(V_w\) = volume of water, and \(V_{sp}\) = volume of superplasticizer.

Three cube specimens with 75 mm size, 3 beam specimens with 75 mm x 75 mm x 350 mm size, and 3 cylinder specimens with 50 mm diameter and 100 mm high were prepared. The specimens were then cured in water. The compressive strength, flexural strength, and splitting tensile strength tests were performed on the cube specimens, beam specimens, and cylinder specimens, respectively, at the age of 7 days.

3. Results and discussion

3.1. Properties of composed materials

The bulk density and the specific gravity of sand, diatomaceous earth binder, and iron ore binder used in this study are summarized in Table 1. The particle size distribution of solid materials in this study is shown in Figure 1. The particle size of the sand ranges from 0.575 µm to 766.2 µm; of the Portland cement ranges from 0.136 µm to 88.48 µm; of the diatomaceous earth binder ranges from 0.107 µm to 231 µm; and of the iron ore binder ranges from 0.107 µm to 231 µm. The specific gravity of the iron
ore binder is almost the same as that of Portland cement. However, the specific gravity of diatomaceous earth is lower than that of Portland cement.

**Table 1.** Density and the specific gravity of sand, diatomaceous earth binder, and iron ore binder.

| Materials             | Bulk density (kg/m³) | Specific gravity |
|-----------------------|----------------------|------------------|
| Sand                  | 1482                 | 2.453            |
| Diatomaceous earth binder | 928               | 2.180            |
| Iron ore binder      | 1211                 | 3.571            |

**Figure 1.** The particle size distribution of the materials.

3.2. Mix proportion of RPC

The mix proportion of RPC is shown in Table 2. In mixture #1, the weight of the iron ore binder was found of 10% of the weight of cement. Since the weight of cement in mixture #2 and #3 was reduced and the weight of iron ore binder was maintained constant, the iron ore binder to cement ratio increased. The comparisons between mixture gradation and target curve based on Modified Andreasen and Andersen Model for mix #1, mix #2, and mix #3 are shown in Figure 2, Figure 3, and Figure 4, respectively. The gradings of all mixture closed to the target curve. Even though the weight of cement was replaced by 5% and 10% for mix #2 and mix #3, the good grading as mix #1 was found. For a particle size less than 10 μm, a little bit different which is about 3% was found. This means that the mixture in this study has less particle finer than 10 μm. The use of finer particles in the RPC mixture with calcined diatomaceous earth powder will be studied in the future.

**Table 2.** The mix proportion of materials for 1 m³ fresh RPC.

| Materials             | Mix #1 (kg) | Mix #2 (kg) | Mix #3 (kg) |
|-----------------------|-------------|-------------|-------------|
| Cement                | 872.00      | 828.40      | 784.80      |
| Sand                  | 1220.80     | 1220.8      | 1220.8      |
| Diatomaceous earth binder | 0.00        | 43.60       | 87.20       |
Iron ore binder 87.20 87.20 87.20  
Water 174.40 174.40 174.40  
Superplasticizer 13.08 13.08 13.08  

Figure 2. Comparison between the mix #1 grading and the target curve.

3.3. Properties of fresh RPC
The properties of fresh RPC are shown in Table 3. Replacing the partial cement content with diatomaceous binder causes the reduction of the relative slump. This is because of the higher absorption of the diatomaceous binder. The fresh RPC with diatomaceous binder has lower air content.

| Fresh RPC Properties | Mix #1 | Mix #2 | Mix #3 |
|----------------------|--------|--------|--------|
| Relative slump flow  | 3.91   | 3.49   | 3.20   |
| Air content (%)      | 0.81   | 0.74   | 0.76   |

3.4. Properties of hardened RPC
The average compressive strength, flexural strength, and splitting tensile strength of all mixtures at the age of 7 days are shown in Table 4. The RPC with diatomaceous earth powder has the lower 7 days compressive strength, but high flexural strength and splitting tensile strength. The higher flexural strength and splitting tensile strength in concrete make concrete structures experience cracking at a greater load [27]. The concrete strength at the age of 28 days and more will be studied in the future.
Figure 3. Comparison between the mix #2 grading and the target curve.

Figure 4. Comparison between the mix #3 grading and the target curve.
Table 4. Seven days average strength of RPC.

| Hardened RPC Properties                  | Mix #1     | Mix #2     | Mix #3     |
|-----------------------------------------|------------|------------|------------|
| Compressive strength (MPa)              | 80.21      | 65.41      | 72.73      |
| Flexural strength (MPa)                 | 7.63       | 8.15       | 7.78       |
| Splitting tensile strength (MPa)        | 10.13      | 11.06      | 9.37       |

4. Conclusion
The mix design of reactive powder concrete (RPC) containing diatomaceous earth binder and iron ore binder is studied. The proportion of the materials was determined based on the Modified Andreasen and Andersen Model. Without using the diatomaceous earth binder, the cement content was 873 kg/m³ concrete volume. The iron ore binder was 10% of the cement content. The cement was then replaced by diatomaceous earth by 5% and 10%. The good correlation between the mixture gradation and target curve was found except for the particles finer than 10 μm, which have a difference of about 3%. The adding of diatomaceous earth binder reduces the workability, air content, and 7 days compressive strength of RPC, but increases 7 days flexural strength and splitting tensile strength. The concrete strength at the age of 28 days and more will be studied in the future.

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