Powder Materials and Their Effect on the Behaviour of Self-Compacting Concrete in Malaysia

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Abstract. This paper discusses the effect of powders on the properties of self-compacting concrete. Fillers like kaolin, limestone, metakaolin and fly ash pozzolans are used by weight to prepare 17 different mixtures of mortar. In addition, four concrete mixes were made to study the effect of filler on shrinkage concrete mixes. From the series of experiments conducted, it has been found that 20% replacement of sand with limestone produces an enhanced strength and stability of the mix with low water absorption compared to the same water to powder ratio in the early stages. The combination of kaolin, primarily enhance the stability of mixture and fly ash enhance the rheology characteristics and hence the compressive strength. The replacement of 10% meta-kaolin provides a very high strength improvement compared to reference mix minimizing water absorption. The use of powders gave good workability and strength and thus would reduce of the use chemical admixtures and cement and consequently reduce the cost. The concrete mixes with fly ash and limestone powders gave better hardened properties with low cost compared to the reference mix.

1. Introduction

One of the revolutionary discoveries in the concrete industry in last two decades is the introduction of Self Compacting Concrete (SCC). It has got the most delightful property of flowing by its own weight. Hence it fills all voids in the formwork and covering bars completely without bleeding or segregation. The advanced research on the factors affecting the flow properties of SCC became highly significant in the modern times.

The mortar constitutes the major part of SCC due to the increased amounts of powders and sand aggregate ratio comparing to reference concrete. Due to this mortar highly influences the characteristics of SCC. Since the mortar is the integral part of SCC mixture, in depth knowledge on the characteristics of mortar is crucially important in SCC design. The presence of mortar provides lubrication between particles of coarse aggregate and good fluidity preserving stability of the mixes. The stability of mixes can be kept by three ways utilizing viscosity by modifying admixtures or raising the powder content up or both [1]. The study on the characteristics of powders on SCC attains great importance. According to EFNARC [2] the mineral admixtures can be classified into an inert filler powders such as quarry dust, pigment, limestone, etc. The Ca(OH)₂ reacts with pozzolanic materials to produce C-S-H. The products are fly ash, meta-kaolin, rice husk ash, silica fume, etc. H.Moosberg-Bustnes et al. [3] divided the effect on powders to the properties of concrete into three types as filler effect, chemical reaction effect and filler-chemical effect.
In the design of mixture, the physical characteristics like shape, particle size distribution and fineness of powders should be considered. If the surface areas of powder particles are less than the surface area of cement particles, more water is required to maintain the same workability. It was reported by Burak et al. [4] that the optimal dosages of powders are based on their physical and physico-chemical properties. These characteristics have an important effect on the properties of the fresh concrete. These properties are particle size distribution, shape of particles, fineness of particles and surface porosity. Often it becomes difficult to recognise these factors as they overlap each other [4].

The addition of limestone powder in concrete (especially C₃S) at early stages will accelerate hydration of cement particles Ramachandran [5]. The C₃A in cement reacts with carbo-aluminate on the surface of C₃A. It was observed by H.G.Ellerbrock [6] that the addition of limestone powder will increase the packing density of cement particles. The lime stone acts as a nucleation sites for calcium hydroxide Bonavetti [7].

2. Experimental work

2.1. Materials

Three different types of powder material are utilised in this research, namely Type 1 ordinary Portland cement, kaolin and fly ash. The physical and chemical properties of these powders are shown in Table 1. The particle size distribution of the materials is indicated in Figure 1. A modified polycarboxylate super plasticising admixture with 30% water content and a specific gravity of 1.05 is used. One of mix constituents is silica sand with a water absorption of 0.35%, specific gravity of 2.64 and fineness modulus of 2.4 is used. The particle size distribution of the fine aggregate is shown in Figure 2. The coarse aggregate used is crushed granite with single size which is between 9.5 to 4.75 mm.

Table 1. Chemical composition and physical properties

|   | Analysis  | Al₂O₃ | SiO₂ | CaO  | Fe₂O₃ | MgO | SO₃ | K₂O | Specific gravity | Fineness m²/kg |
|---|-----------|-------|------|------|------|-----|-----|-----|----------------|----------------|
|   | Cement    | 5.72  | 15.3 | 72.37| 3.33 | -   | 1.15| -   | 0.62           | 390            |
|   | Fly ash   | 30.7  | 48.2 | 8.31 | -    | -   | 0.78| 1.06| 2.27           | 469            |
|   | Metakaolin| 41.4  | 54.5 | 1.15 | 2.41 | -   | 2.12| -   | 2.72           | 547            |
|   | Limestone | 40.40 | 55.4 | 1.21 | 2.9  | -   | 2.58| -   | 2.72           | 748            |
|   | Kaolin    | 41.4  | 54.5 | 1.15 | 2.41 | -   | 2.12| -   | 2.72           | 547            |

Figure 1. Particle size distribution of powders

Figure 2. Grading of sand
2.2. Mix proportion
EFNARC [2] guidelines are adopted to design the mix proportion of this study. Table 2 lists the mix proportions of the mortar mixes.
After choosing the optimum replacement level of powders in mortar mixes, the proper mix proportions of concrete mixes with 10 mm single sized coarse aggregate were used with three different types of mineral admixtures. The details of the mixes are described in the Table 3 and the mix proportions are shown in Table 4.

| Table 2a. Mortar mix proportions (4 litres) |
|-------------------------------------------|
| Symbol | B/W | Cement (Kg) | Fly ash (Kg) | Metakaolin (Kg) | Sand (Kg) | Limestone powder (Kg) | Kaolin (Kg) | Water (Kg) | SPD (% of powder weight) |
|--------|-----|-------------|--------------|----------------|----------|----------------------|------------|-----------|-------------------------|
| C      | 0.32| 3.29        | 0            | 0              | 4.94     | 0                    | 0          | 1.0528 | 1.1 |
| 5FA    | 0.32| 3.125       | 0.165        | 0              | 4.92     | 0                    | 0          | 1.0528 | 0.8 |
| 10FA   | 0.32| 2.962       | 0.329        | 0              | 4.85     | 0                    | 0          | 1.0528 | 0.7 |
| 15FA   | 0.32| 2.797       | 0.494        | 0              | 4.80     | 0                    | 0          | 1.0528 | 0.65 |
| 20FA   | 0.32| 2.632       | 0.658        | 0              | 4.75     | 0                    | 0          | 1.0528 | 0.6 |
| MK5    | 0.32| 3.125       | 0            | 0.165          | 4.94     | 0                    | 0          | 1.0528 | 1.6 |
| MK10   | 0.32| 2.962       | 0            | 0.329          | 4.90     | 0                    | 0          | 1.0528 | 2 |
| MK15   | 0.32| 2.797       | 0            | 0.494          | 4.87     | 0                    | 0          | 1.0528 | 2.5 |
| MK20   | 0.32| 2.632       | 0            | 0.658          | 4.85     | 0                    | 0          | 1.0528 | 2.5 |
| LP5    | 0.32| 3.29        | 0            | 0              | 4.69     | 0.247                | 0          | 1.0528 | 1.2 |
| LP10   | 0.32| 3.29        | 0            | 0              | 4.446    | 0.494                | 0          | 1.0528 | 1.4 |
| LP15   | 0.32| 3.29        | 0            | 0              | 4.199    | 0.741                | 0          | 1.0528 | 1.6 |
| LP20   | 0.32| 3.29        | 0            | 0              | 3.952    | 0.988                | 0          | 1.0528 | 1.4 |
| K5     | 0.32| 3.29        | 0            | 0              | 4.69     | 0                    | 0.247      | 1.0528 | 1.3 |
| K10    | 0.32| 3.29        | 0            | 0              | 4.446    | 0.494                | 0          | 1.0528 | 1.8 |
| K15    | 0.32| 3.29        | 0            | 0              | 4.199    | 0.741                | 0          | 1.0528 | 2.3 |
| K20    | 0.32| 3.29        | 0            | 0              | 3.952    | 0.988                | 0          | 1.0528 | - |

| Table 3. Details of concrete mixes |
|-----------------------------------|
| Symbol | Replacement level (%) | Replacement type | Max. Size of coarse agg. |
|--------|----------------------|------------------|-------------------------|
| CS10   | -                    | -                | 10                      |
| FA10S10| 10                   | Fly ash          | 10                      |
| MK10S10| 10                   | metakaolin       | 10                      |
| LP20S10| 20                   | limestone        | 10                      |

| Table 4. Mix proportion of concrete mixes |
|------------------------------------------|
| Symbol | W/B | C (kg/m³) | FA (kg/m³) | MK (kg/m³) | F.Aggr. (kg/m³) | LP (kg/m³) | C.Aggr. (kg/m³) | SPD (% of powder weight) |
|--------|-----|----------|-----------|-----------|----------------|-----------|----------------|-------------------------|
| CS10   | 0.32| 520      | -         | -         | 832            | -         | 861            | 1.1                     |
| FA10S10| 0.32| 468      | 52        | -         | 824            | -         | 853            | 0.7                     |
| MK10S10| 0.32| 468      | -         | 52        | 828            | -         | 859            | 2                       |
| LP20S10| 0.32| 520      | -         | -         | 666            | 166       | 866            | 1.4                     |

2.3. Mixing and testing
A bowl mixer was used to mix the constituents of self-compacting mortar. The fluidity of mortar is evaluated by using mini V-funnel box and mini slump flow cone tests and according to EFNARC guidelines [2]. Each mix has 21 specimens which are prepared in steel moulds. The dimensions of these moulds are 50X50X50mm, polythene sheet are used to cover these moulds to prevent evaporation of water from specimens. These specimens are demoulded after one day and immersed into curing tank to the time of the test. A Pan mixer which was used to mix of self-compacting concrete has 0.1 m³ capacity. Compressive strength tests are used to evaluate the hardened properties of concrete samples and tests were conducted according to BSI (1983c) [10].

3. Results and discussions

3.1. Effect on workability

The limestone powder mixes at the same w/p of the plasticiser and results of slump flow are illustrated in Figure 3. It has been observed that the increase in replacement percentage leads to decrease in slump flow. However, exception has been noted of LP20 which has shown an increase in spread of slump flow. In addition to the above the flow time increases with an increase in replacement level of limestone powder as shown in Figure 4. This may be due to the improved packing density of powder and reduction in the voids and its percentage decreasing the entrapped water in the mortar skeleton which is true for all except LP20.

The results of the slump flow spread and flow time of kaolin mixes with the w/p ratio of 0.32 and super plasticiser dosage of 2% is shown in Figures 3 and 4. There is a decrease in the flow spread and an increase in the flow time is indicated by increasing the replacement level. This is due to the increasing yield stress and viscosity of the mortar. When the super plasticiser dosage 2% of the optimum for the K5 and K10 mixes leads to excessive bleeding for the K5 mix. When kaolin is used as a partial replacement of sand improves the stability of self-compacting mortar and becomes more cohesive. This is due to the antiparticle friction between the plates like structures.

The effect of mixes with different replacement levels of fly ash with the same water to powder ratio and super plasticiser dosage are shown in Figures 3 and 4. It was observed that the slump flow spread is higher while the flow time of the mini V-funnel box is lower. This is due to the result of decrease in viscosity of the paste as the replacement level is increased. Increasing the replacement level of the volume of fly ash will give lower mortar density as the specific gravity of fly ash is lower than cement. The fly ash has a spherical shape which enables particles to roll over one another [11] reduces the inter-particle friction increasing the fluidity of the paste.

The results obtained for the slump flow of meta-kaolin mixes at the same super plasticiser dosage is illustrated in Figure 3. It has been observed that at the super plasticiser dosage, the increase in the replacement level of meta-kaolin leads to a decrease in the flow ability of mixes at the same w/p ratio. In Figure 4, the flow time results of mixes with increasing replacement level of meta-kaolin is illustrated. The irregular shape of the particles generates high frictional forces which leads to a decrease in flow ability of mixes.

![Figure 3](image-url)
3.2. Effect on strength of mortar

The compressive strength increases with age. The development of this phenomena is presented in Figures 6, 8, 10 and 12. The replacement percentage of LP with sand, results in higher strength compared to control mixture C and is illustrated in Figure 5. The increase in replacement of LP mixes results in greater strength. This strength increase occurs due to two reasons. The limestone powder acts as a filler (Physical effect) due to its superior fineness compared to the fineness of cement. These superior finer particles fills the voids between the cement particles and increases packing density and subsequently provides high strength and durability. The presence of limestone powder initiates hydration reaction of cement compounds (C₃S and C₃A). Previous research Ramachandran [5] showed that hydration ratio of C₃S will accelerate due the addition of more LP. It can be concluded that the limestone has a physico-chemical effect. The mix of LP20 is the optimum mix with greater strength.

Figure 4. Flow time of different powder mixes with same w/p ratio and superplasticizer dosage

![Flow time of different powder mixes](image)

Figure 5. Compressive strength of limestone powder mixes

![Compressive strength of limestone powder mixes](image)

It is evident from the Figure 6 that adding kaolin as a replacement of sand decreases the strength compared to the control mix. The strength of kaolin is low even though the silica content is high. This could be due to the octahedral layer structure of kaolinite, which are centered on aluminium cat ion, in hydroxyl groups on their external surfaces which do not interact strongly with the hydroxyl ions in cement [8]. It has been also observed that, increase in the dosages of kaolin leads to reduction of strength at 90 days. As shown in Figure 8 the difference in strength of the K5 and Control mixture decreases with the increase in age until they are almost the same at 90 days.

Figure 6. Compressive strength of kaolin mixes with age

![Compressive strength of kaolin mixes](image)
The fly ash mixture shows higher strength than the control mixture for all mixtures except that of 90 days. This is clearly illustrated in Figure 7. The reason is due to the presence of calcium hydroxide in the cement paste. This calcium hydroxide reacts with fly ash to form calcium silicate gel increasing the compressive strength. At early stages (around 3 days) FA15 provided strength lower than the fly ash mixes. But FA15 provided high strength at 14 days when compared with FA5 and FA20. Hence the optimum mix for high strength is FA10 as is clear from Figure 10.

![Figure 7. Compressive strength of fly ash mixes with age](image)

The pozzolanic activity of Meta kaolin mixes are indicated in Figure 8. Meta-kaolin mixes (MK5, MK10 and MK15) shows a good strength achievement compared with the control mix. At this stage the optimum dosage of meta-kaolin is 10%. The cement replaced by met-kaolin has a significant effect on the hydration of Portland cement. The Ca(OH)₂ produced during the cement hydration reacts with meta-kaolin leads to an augmentation in the densification of interfacial transition zone. The improvement in the density at the transition zone leads to a better bonding strength and thus the micro cracking is decreased. The initiation of micro cracking takes place at high stress level which agrees with the findings of Aulia [12].

![Figure 8. Compressive strength of metakaolin mixes with age](image)

3.3 Effect on strength of concrete
The strength development for control, filler and pozzolan mixes up to 180 days is shown in Figure 9. It can be observed that limestone mixes enhance the strength in the long term more than the control and pozzolanic mixes this is shown in Figure 9. This is due to the combined effect of physical and chemical properties of limestone as mentioned in (3.4). After 1 day limestone mixes exhibit a higher relative strength than after 28 and 180 days. In addition, as the age increases, the relative strength decreases. For example, after 1 day, the relative strength of LP20C10 is 1.52 but as age increases and especially at 28 days the relative strength became 1.47 and 1.31 at 180 days as shown in Figure 16. This agrees with Nehdi [13]
The pozzolanic effect of fly ash and metakaolin on compressive strength is apparent from the results and is shown in Figure 9. After 1 day, the strength of metakaolin mixes is low as when compared with the relative strength of 28 days. This is in agreement with Al-jabri [14]. This is due to high dosage of superplasticizer of metakaolin mixes. In addition, the pozzolanic activity at the early ages is small. After 28 days the percentage increase is higher than after 1 and 180 days which could be due to the pozzolanic activity of metakaolin, as mentioned in (3.4). According to Fook [15], with time the difference in compressive strength between metakaolin mix and control mix is smaller. This is mainly attributed to the fact that the reaction between cement hydration products and metakaolin at the later ages is slowed down with time due to the completion of the reaction processes in metakaolin mixes. Wild et al. [16] reported that metakaolin improves the strength of mixes because it acts as filler as well as its role in accelerating the cement hydration.

The strength of fly ash mixes at 1 day is slightly higher than metakaolin mixes which could be attributed to the fact that metakaolin mixes have a high dosage of superplasticizer which may delay the cement hydration; and this has been reported by Hassan [17]. After 3 days, the compressive strength of fly ash mixes is lower than metakaolin mixes due to the fact that the particle size of fly ash is coarser than the particle size of metakaolin. This means that the required surface area for pozzolanic reaction is lower and thus the strength would be less. In addition, Figure 9 also indicates that metakaolin mixes give strength higher than fly ash mixes and this is contrary to the mortar mixes. This could be due to the fact that the paste content in fly ash mixes is higher and aggregate content is less compared that in metakaolin mixes and thus the transition zone is less.

**Figure 9.** Compressive strength development for different mineral admixture mixes

**4. Conclusions**

Analysing the results presented above, the conclusions which are drawn from the study are summarised below:

1. By adding suitable powder materials as mineral admixtures, self-compatibility of mortars can be obtained. A sufficient balance between flowability and viscosity also is obtained by adding mineral admixtures.
2. Adding fillers like LP and K provides adequate stability to the mixes.
3. The increased replacement of FA cement increases the flowability of mixes.
4. The workability and strength increases with an optimum 10% replacement of FA and MK. An optimum replacement level of limestone 20% also found to increase workability. Moreover, kaolin mixes do not give positively results.
5. The strength decreases with an increase in the replacement level of FA and MK after 10%. The strength increases with increase in replacement of LP.
6. The use of limestone powder in the mixes gave compressive strength better than the pozzolan and control mixes. Moreover, the percentage increase in the strength of limestone mixes decreased with age.
7. Metakaolin concretes had compressive strength higher than fly ash concretes.
8. The use of powders gave good workability and strength and thus would reduce the use of chemical admixtures and cement and consequently reduce the cost.
9. Finally, fly ash and limestone mixes gave a good flowability and strength.

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