The potency of metakaolin as addition material in high strength self-compacting concrete to increase Modulus of Rupture (MOR) in rigid pavement application

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Abstract. This study focused on the modulus of rupture (MOR) for high strength self-compacting concrete (SCC) using varied metakaolin (MK) composition. The MOR significantly contributes to the resilience and mechanical performance of the rigid pavement, and is enhanced by modifying the regular concrete material. In addition, the MK is known to be potentially economical and occurs abundantly as natural resources. Plain concrete beams with dimensions 400 x 100 x 100 mm3, were tested in the laboratory in an effort to measure the MOR from varied MK composition for each specimen or modified concrete type. The result showed the MOR increase is exclusively as a result of additional metakaolin. Also, the newly modified material was proven to offer more advantages when applied as rigid pavement material. Furthermore, the analytical laboratory result showed the optimum MK dosage was estimated at 20% of the binder weight. This subsequently enhances the MOR by 17.28% compared to non-MK concrete.

1. Introduction

Several countries today apply rigid pavement is an alternative in road construction, although the structure is less convenient during driving compared to a flexible pavement. However, the situation is economically more profitable. For these reasons, rigid pavement has been widely applied in recent times.

Therefore, the application of concrete is known to significantly support the performance of this type of structure. Furthermore, tensile strength and modulus of elasticity are two properties of concrete influencing construction capacity [1].

Recently, the use of self-compacting concrete appears to be more frequent and widespread in the construction industry. This is obviously attributed to the ease of adaptability of the mould apart from the complex nature of steel reinforcement. In addition, this category of concrete provides an almost perfect homogeneity with the ability to compress without a vibrator [2].

Improved material quality is necessary measure in boosting high SCC performance. This is achieved by including the admixture, e.g., pozzolanic. However, the pozzolanic admixture in form of metakaolin is applied in this study.

The purpose of the research, therefore, is to improve the quality of high strength self-compacting concrete, specifically in modulus of rupture, by studying the effects arising from the addition of metakaolin composition in concrete mixture as a substitute for Portland cement. Furthermore, the conclusion highlights these influences on the modulus of rupture for a 28 day period. Based on the
equation from previous studies, a clear relationship existing between the varied metakaolin in high strength concrete and its performance, especially the MOR increase, simultaneously satisfies the criteria of self-compacting concrete.

The enhanced MOR tend to influence the service life span of the structure. Previous investigations affirmed the relationship between the number of load repetition and increasing MOR. Furthermore, the scientific confirmation produce empirical evident indicating the inclination further influenced the fatigue capacity of the rigid pavement subjected to cyclic loading [3].

2. Literature review

Metakaolin is a known pozzolanic material manufactured from selected kaolin after refinement and calcination under specific conditions. This substance is a highly efficient pozzolan and reacts rapidly with excess calcium hydroxide to produce calcium silicate hydrates and calcium alumina silicate hydrates [4]. In addition, the material is used to improve the concrete quality by enhancing the strength and reducing setting time, and also demonstrates as a promising material for the manufacture of high performance concrete [5].

The modulus of rupture, also called flexural strength, is the maximum tensile strength achieved theoretically at the bottom of the specimen. This value depends on the sample dimension, load arrangement, and is represented in ACI 318 as 0.62 $\sqrt{f'c}$.

The mixtures containing metakaolin have been confirmed to foster compressive force, tensile split, and enhanced flexural strength, and elastic modulus compared to control mixtures [6]. The application of concrete materials in rigid pavement construction is extensive comprising local to federal road networks. Meanwhile, some of the associated problems include processes involving long traffic period, certain sub-grade types of soil with different responses, unpredictable failure / damage occurrence, and also the behaviour of the rigid pavement plate structure known to be an indecisive variable. Furthermore, several factors apparently need to be studied through research and direct field observation.

Several country codes show the use of steel reinforcement in concrete-base rigid pavement is not compulsory. However, practically / empirically proven reinforcement tends to prevent damage or structural failure, particularly on subgrade, known as an expansive soil type. This is related to some equations developed by rigid pavement researchers, including Roesler [3] and Rao [7]. The magnitude of the flexural capacity possibly influences the structural performance. Also, the service life span is greatly influenced by the concrete quality.

3. Material Composition

Ordinary Portland Cement (OPC) type 1 conforming to SNI 15-2049-2004, ASTM C150-12, and EN 197-1:2011 was used. Table 1 summarizes the physical and chemical properties of the cement.

| Composition (%) | Specific Gravity | Appearance |
|-----------------|------------------|------------|
| CaO 63.85       | Al₂O₃ 5.79       | MgO 2.86   | Fe₂O₃ 2.47 | Alkali Oksida 1.4 | SO₃ 1.73 | 3.13 Grey |

The aggregates materials employed include sand with maximum size of 4.75 mm, gravel with maximum size of 10 mm and the minimum size of 6.3 mm. The choice of small size aggregates is considered to satisfy SCC characteristics and also attain high compressive strength.

The Concrete mixture designed to achieve the SCC compressive strength is more than 40 MPa. A super plasticizer content of 1.9% was used for water tightness and workability retention. Also, metakaolin was then added to the composition. The chemical admixture was reported chloride-free and the base of the proportion represents the binder weight.
Resume of the mixture proportion of all material included in SCC show in Table 2 as below:

| Metakaolin Variation (%) | Metakaolin (kg) | Cement (kg) | Water (L) | Superplasticizer (L) | Fine Aggregates (kg) | Coarse Aggregates (Kg) |
|--------------------------|-----------------|-------------|-----------|----------------------|----------------------|-----------------------|
| 0                        | 0               | 600         | 186.0     | 11.40                | 821.98               | 802.67                 |
| 12.5                     | 75              | 525         | 186.0     | 11.40                | 815.96               | 796.79                 |
| 15                       | 90              | 510         | 186.0     | 11.40                | 814.76               | 795.62                 |
| 17.5                     | 105             | 495         | 186.0     | 11.40                | 813.55               | 794.45                 |
| 20                       | 120             | 480         | 186.0     | 11.40                | 813.28               | 793.27                 |
| 22.5                     | 135             | 465         | 186.0     | 11.40                | 812.07               | 792.09                 |

The mixed design was achieved by replacing a portion of cement with metakaolin on the basis of cement weight percentage and by maintaining the overall binder weight. The equipment used include the testing equipment for concrete material, oven, a set of scales and mixing of concrete, Abrams cone and flow table to measure the slump diameter, L-Box, V-funnel, mould, water bath for concrete treatment, and universal testing machine.

4. Test Specimens and Experimental Program

The laboratory experiment conducted aimed at evaluating the serial measurement on specimens. In the early stage, the concrete is observed to ascertain the fulfilment status based on SCC characteristics. The specimens were tested with fresh concrete to determine the parameter of filling, passing, and segregation resistance by doing slump flow, L-Box, and V-funnel test. Then, the resulting sample is moulded to create other type of specimens for hard concrete measurement i.e. compressive strength, modulus of elasticity and rupture.

X-ray fluorescence analysis was performed in order to evaluate the chemical composition of metakaolin. The result showed the amount of silicate oxide present, and other compounds with the tendency to improve compressive strength.

The testing of SCC parameters with fresh concrete was carried out based on EFNARC 2005 in the form of Slum Flow, L-box and V-funnel to ensure the SCC characteristics are attained. Figure 1a, 1b and 1c show the instruments used for determining of SCC parameters.

Figure 1a. Slum flow test instrument
Several examination conducted include compressive strength and elastic modulus of SCC. These were intended to determine the quality of hard concrete associated with the ability to endure compressive stress and also the rigidity in elastic phase. The universal testing machine was employed to obtain the output in the form of maximum stress and elastic modulus.

The modulus of rupture analysis was performed using a three-point loading method, where the load was positioned at the center of the specimen’s span. The test was carried out by placing the specimens with the size of 400 mm x 100 mm x 100 mm on two support with effective span of 300 mm, and then assigned a load at the center until the maximum load is reached.

The test specimens comprised of beams placed in moulds of dimension 400 mm x 100 mm x 100 mm. In addition, 5 samples were assigned to a single metakaolin variation content, and were withdrawn after 2 days for a 21 day treatment in a water bath. Further purification was extended to reach 28 days in open air. Finally, the specimens were then passed through the universal testing machine to determine the modulus of rupture.

The calculation of modulus of rupture of the specimens with three-point loading method:

$$\sigma = \frac{3P}{2bd^2}$$

Where \( \sigma \) is Modulus of rupture (Mpa), \( P \) is Maximum load (N), \( L \) is span length of specimen (mm), \( b \) is width of specimen (mm) and \( d \) is height of specimen (mm)
5. Results and discussion
Considering the metakaolin was a result of natural mining, there is the necessity to conduct an analysis to determine the certainty of the constituent chemical compound assumed to contribute significantly in the improvement of concrete quality. Table 3 shows the chemical compound of metakaolin as a result of X-ray fluorescence testing.

The composition of SiO$_2$ is dominant in MK and shows the potency to improve concrete quality. This works to complement the cement containing mainly CaO. Furthermore, the hydration reaction of cement and water tend to be optimal as a result of available and sufficient silica oxide. This provides best concrete pavement outcome and high compressive strength. However, the excessive amount of MK does not linearly contribute to the strength of the concrete, but adversely lead to a decline. The unused MK automatically functions as an unreactive binder with the possibility to degrade the concrete.

### Table 3. X-Ray fluorescence analysis

| Composition | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | K$_2$O | P$_2$O$_5$ | SO$_3$ | Cl | TiO$_2$ | MnO | CeO$_2$ |
|-------------|---------|-------------|-------------|------|--------|------------|--------|----|---------|------|---------|
| %           | 65.00   | 15.02       | 5.41        | 5.24 | 3.43   | 2.04       | 1.52   | 1.26 | 0.50    | 0.18 | 0.10    |

5.1. Compressive Strength
The presence of MK influences the chemical reaction between water and cement. Silica oxide content in MK also help to create a gel in matrix of paste. This contributes in enhancing the concrete strength. Table 4 shows the maximum addition of MK is 17.5% from the binder weight. Furthermore, the study also proved the MK is able to maintain the properties of the mixture based on self-compacting concrete characteristics [8].

### Table 4. Compressive strength

| Metakaolin Variation (%) | 0  | 12.5 | 15 | 17.5 | 20 | 22.5 |
|--------------------------|----|------|----|------|----|------|
| Compressive Strength (Mpa)| 46.80 | 50.09 | 51.60 | 59.70 | 51.98 | 45.20 |

5.2. Modulus of Rupture (Flexural strength)
Table 5 shows the results of the average modulus of rupture analysis as follows:

### Table 5. Modulus of Rupture (MOR)

| Metakaolin Variation (%) | 0  | 12.5 | 15 | 17.5 | 20 | 22.5 |
|--------------------------|----|------|----|------|----|------|
| Modulus of Rupture (Mpa)  | 4.53 | 4.90 | 4.91 | 5.12 | 5.31 | 6.24 |

Previous researches reported the use of concrete as a road pavement material required concrete quality with tensile strength limits ranging from 3 to 4 MPa. This shows the results of the study are in accordance with Table 5, and the concrete with the addition of MK shows superior properties beyond the strength limit of ordinary concrete [9].

5.3. Rigid Pavement Application
The maximum tensile stress limit and Modulus of elasticity determines the characteristics of SCC with MK added material in rigid pavement construction. Using finite element analysis, it could be showed the maximum MOR when rigid pavement have been subjected to static load.
Table 6. Different result of MOR appearance in rigid pavement.

| Thickness of Plate (mm) | Tensile Stress (Mpa) | Deflection under point load (mm) | Deflection at mid span plate (mm) |
|-------------------------|----------------------|---------------------------------|----------------------------------|
| 250                     | 1.18                 | 0.80                            | 0.30                             |
| 150                     | 3.66                 | 1.31                            | 0.16                             |
| 100                     | 9.62                 | 3.37                            | 0.47                             |

The tensile stress generally occurred just below the working point at static load, while the maximum tensile stress followed at similar point, although this does not exceed the tensile capacity of the material[10]. For instance, a rigid plate with varied thickness of 50, 100, 150 mm and a size of 3.5 x 4.5 m$^2$ and load of 50 kN produced the following structural response as showed in Table 3.

Figure 2. Finite element analysis of single slab rigid pavement

Table 6 and Figure 2 indicate the response of the concrete slab corresponds to the strain energy theory. Strain distribution is a representation of the structural response to the applied external load. Maximum stress in the form of tensile stress occurred just below the load point worked on the edge of the concrete slab as well as the maximum deflection. Subsequently, the safety limit of the rigid pavement concrete slab was then determined. By limiting the tensile stress in the slab to be less compared to the permit of the concrete material used, a rigid pavement design based on performance is possible to conduct [11][12].

6. Conclusion
The results showed the enhanced tensile strength of concrete materials contributed significantly in improving the performance of rigid pavement slabs. The conclusions were summarized are as follows:

Metakaolin tends improve the properties of concrete materials at the right amount of addition to nearly 17% of the binder weight. Further inclusion showed a possible reduction in the ease of workmanship. This decline extends to the compressive strength, elastic modulus and tensile strength.

The use of concrete with added MK material also increased the tensile strength. Therefore, the high potential in rigid pavement application, considering the addition of tensile strength, greatly influenced the thickness of the structure.

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