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Strength of Self-Compacting Concrete Containing Metakaolin and Nylon Fiber

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Abstract. In Malaysia, issue to attain durable concrete structures has risen due to shortage of skilled labours. Besides pollution due to construction activities, safety and health of the workers is also a major concern. Self-compacting concrete is able to overcome the problems through its execution. Moreover, properties of SCC can be further improved via incorporation with other materials. Thus, this study was conducted to investigate the strengths and water absorption of SCC containing metakaolin (MK) and nylon fiber (NF) besides determining the effects of MK and NF in SCC. Four mixes (100%C, 95%C 5%MK, 100%C 0.5%NF, 95%C 5%MK 0.5%NF) were being carried out with w/c ratio 0.4 and 1.5% super-plasticizer (SP). Fresh concrete were tested with slump flow, T500 and segregation resistance test whereas hardened concrete were tested with compressive, tensile and flexural strength test. The results of fresh SCC were consistent as all mixes mostly falls in the same class for each respective test. Based on compressive strength test, all mix proportions were able to reach at least 80% of targeted strength, 50MPa. SCC (95%C 5%MK) had the highest compressive, split tensile and flexural strength. While SCC (95%C 5%MK0.5 %NF had better testing results compare to 100%C 0.5%NF.

1. Introduction

Construction industry does not only have to produce buildings possesses strong structures in shortest time possible but also with remarkable exterior fulfilling aesthetical value. However, shortage of skilled workers has become the greatest challenge faced by construction industry in Malaysia [1]. Conventional concrete may not reach the expected strength due to defective of workmanship caused by shortage of skilled labours. Self-compacting concrete (SCC) with its high flow ability, passing ability and stability is able to overcome the difficulties faced by conventional concrete.

SCC is a highly flowable, non-segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation [2]. It was first developed in Japan at 1988 to achieve durable concrete structures due to gradual declination of skilled labours [3]. As compared to conventional concrete, it is more desirable because of faster construction, reduction of manpower, better durability, lesser noise levels, no vibration and safer working environment [4]. Besides, it could be incorporated with raw material such as mineral admixture and fibers to satisfy specific performance.

This study is conducted to investigate the strength of SCC containing metakaolin and nylon fiber and determine the effects of both materials in SCC. Four concrete mixes including a controlled mix was carried out to satisfy the objectives of the study. Fresh properties of SCC was determined via slump flow, T500 and segregation resistance test. Meanwhile, mechanical properties of SCC was verified via compressive strength, split tensile strength, and flexural strength test.

2. Literature review
According to [3], in order to achieve the mechanism of SCC, high deformability of paste and segregation resistance between coarse aggregate and binder during the flow of concrete through the confined zone of reinforcing bars are involved. Through limitation of aggregate content, application of low water/cement ratio (w/c) and use of super-plasticizer (SP), self-compacting of concrete is able to be achieved.

To achieve moderate workability and, at the same time, attain high flow ability of SCC, w/c ratio of the concrete mixes should be set properly. It was discovered that the decrease of w/c ratio in SCC mixes increased the strength of SCC [5-7]. Through employment of SP, concrete is allowed to reduce w/c ratio and enabled to produce SCC through enhancement in workability [8]. Generally, the amount of SP ranges from 0.5% to 3% of cement weight. Addition of SP up to certain amount in concrete mix yields good workability while increasing the compressive strength of concrete itself [9-10].

In addition, SCC incorporates with metakaolin (MK), a processed amorphous silica material obtained from calcination of kaolin is able to further improve its properties [11]. According to Alyhya [8], Portland cement with MK replacement from 5% to 10% has positive effect on concrete bleeding while replacement up to 20% improves permeability resistance of concrete. Early compressive strength and durability of SCC containing MK improves because of cement matrix homogeneity due to replacement of cement with MK. It was discovered that 5% to 20% of MK as cement replacement material improved the compressive strength of SCC linearly [12-13]. Inclusion of 10% MK in SCC mix is able to reach optimum strength in the aspect of compressive, tensile and flexural [12, 14-16].

Besides MK, SCC can also be incorporated with nylon fiber (NF) for secondary reinforcement. [17] defines that NF are spun from nylon polymer and transformed through extrusion, stretching and heating to form oriented crystalline fiber structure. It is good in tenacity, toughness, recovery of elasticity and hydrophilic [17-18]. NF can act as crack arrester by controlling detrimental effects of plastic shrinkage and drying shrinkage [18-19]. It was discovered that addition of NF up to 1% increased the strength of concrete marginally up [19-20].

Several researches had illustrated that incorporation of SCC with mineral admixture and fiber enabled SCC to attain better properties. Vinayak and Mangulkar [21] discovered that mechanical properties of SCC containing silica fume, MK, fly ash as cement replacement material and steel fiber was better than SCC containing only mineral admixture. Besides, by having marble powder, MK and limestone powder as cement replacement, SCC added with fiber had better strength than SCC containing only mineral admixture [22]. Thus, it can be indicated that SCC containing both mineral admixture and fiber have better strength and tensile properties than SCC containing only mineral admixture [21-23].

3. Materials and methods

3.1. Coarse and fine aggregates
Aggregate is defined as granular material of natural, manufactured or recycled origin used in construction [24]. For the purpose of concreting, aggregates used must be oven-dried for 24 hours at temperature of 105°C ± 5°C. For SCC, the maximum size of the aggregates is usually limited to 20 mm [25]. In this study, coarse aggregate used passed sieve size of 14 mm whereas fine aggregate passed sieve size of 5 mm.

3.2. Cement
Cement is a hydraulic binder that forms a paste which then sets and hardens by means of hydration process when mixed with water. After hardening, cement continue retains its strength and stability. In

this study, the cement used was Ordinary Portland Cement (OPC) constituting of 95% to 100% of clinker (K) [26].

3.3. Metakaolin (MK)
Metakaolin (MK) is a largely amorphous dehydration product of kaolinite that exhibits strong pozzolanic activity [27]. It is processed from calcining clay at temperature ranging from 650 to 800°C. When temperature exceeds more than 900°C, MK will undergoes further reactions to form crystalline compounds. In this study, it was used to replace cement in different mixes.

3.4. Nylon fiber (NF)
Nylon Fiber (NF) is one of the synthetic fiber that is spun from nylon polymer and transformed through extrusion, stretching and heating to form an oriented, crystalline fiber structure [17]. It is added in the concrete mix as secondary reinforcement to control cracks due to plastic shrinkage. In this study, manual cutting of NF's filaments into 2 inches length are employed and NF was added into the mixes.

3.5. Super-plasticizer (SP)
Super-plasticizer (SP) is known as High Range Water Reducer (HRWR) as it allows low water cement ratio and at the same time, maintain the workability of concrete [9]. In this study, Dynamon NRG 1030 was used in the concrete mix. It is a white-coloured liquid super-plasticizer which is recommended to be used in concrete that requires low water content [28].

3.6. Mix proportion
Four concrete mixes were carried out and being subjected to experimental analysis. The mix proportion of concrete are presented in Table 1. All mixes had the same water/cement ratio (0.4) and same amount of super-plasticizer (1.5%). The concrete composition was designed to reach a targeted strength of 50MPa.

Table 1: Mix proportion of concrete.

Mix Proportion	Cement (kg/m^3)	Coarse Aggregates (kg/m^3)	Fine Aggregates (kg/m^3)	MK (kg/m^3)	NF (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
Controlled Mix	465.00	820.00	840.00	0.00	0.000	185.00	6.98
95%C 5%MK	441.75	820.00	840.00	13.40	0.000	185.00	6.63
100%C 0.5%NF	465.00	820.00	840.00	0.00	1.50	185.00	6.98
95%C 5%MK 0.5%NF	441.75	820.00	840.00	13.40	1.50	185.00	6.63

3.7. Test on fresh concrete
Slump flow, T_{500} and segregation resistance test were tested on fresh concrete in order to determine the flow ability, viscosity and segregation of each SCC mix [29].

3.8. Test on hardened concrete
Compressive strength, split tensile strength and flexural strength were tested on hardened concrete samples in order to determine the mechanical properties of SCC mix [30]-[33].

4. Results and discussions

4.1. Slump flow and T500
Slump flow and T500 test were conducted in order to determine the fresh properties of SCC. The result of slump flow and T500 are tabulated in Table 2.

Based on the result, the sample of 100%C 0.5%NF had the highest slump flow value which is 570mm. Meanwhile, the sample of SCC with 95%C 5%MK 0.5%NF had the lowest slump flow value which is 556mm. The presence of MK will contribute to the decrease of concrete workability [34]. This is because MK acts as filler that fills the pores in the concrete. However, all casted SCC samples had shared the same flow class which is SF1. SF1 SCC is suitable for various application such as concrete slab of a house, piling and tunnel coating.

Table 2: Slump flow and test T_{500}

Mix Proportion	d_1 (mm)	d_2 (mm)	d (mm)	Slump flow class (SF)	T_{500} (s)	Viscosity class (VS)
Controlled Mix	575	550	562.5	SF 1	2.63	VS 2
95%C 5%MK	575	555	565	SF 1	2.63	VS 2
100%C 0.5%NF	570	570	570	SF 1	2.63	VS 2
95%C 5%MK 0.5%NF	562	550	556	SF 1	2.54	VS 2

On the other hand, the viscosity class for all SCC samples are in the same classification which is VS2. The SCC mixes were more likely to exhibit thixotropic effects which may be helpful in limiting the formwork pressure or improving segregation resistance [29].

For the T_{500} test, SCC sample with 95%C 5%MK 0.5%NF had the fastest time to reach 500 mm diameter which is 2.54s compared to other samples. Meanwhile, the other three (3) samples share the same timing to reach the 500 mm diameter which is 2.63s. According to specification and guideline for self-compacting concrete provided by EFNARC, the minimum time in T_{500} test is 2 second. Therefore, all the SCC samples are meeting the requirement stated by EFNARC in producing the SCC.

4.2. Sieve segregation

The sieve segregation test were conducted to determine the segregation resistance of the SCC produced. Data of the sieve segregation test were tabulated in Table 3.

Table 3: Result of sieve segregation resistance test.

Mix Proportion	Wp (kg)	Wps (kg)	Wc (kg)	Sieve segregation resistance (%)	Sieve segregation resistance class (SR)
Controlled Mix	1.20	1.95	4.81	16	SR 1
95%C 5%MK	1.21	1.98	4.81	16	SR 1
100%C 0.5%NF	1.20	1.95	4.81	16	SR 1
95%C 5%MK 0.5%NF	1.25	0.53	4.81	15	SR 2

By referring to the result, it showed that SCC with 95%C 5%MK 0.5%NF had the lowest percentage of segregation resistance which is 15% compared to other samples which is 16%. SCC that falls in SR1 is suitable to be used in thin slabs and for vertical used with a flow distances less that 5 m and isolation gap of more than 80 mm [29].

For the samples in the class of SR2, the concrete is suitable for vertical used with a distance of more than 5 m and isolation gap of more than 80 mm [29]. Based on the segregation data, it can be concluded that all of the SCC samples are in good quality according to its used in the industry.

4.3. Compressive Strength

For compressive strength test, sample of 100 mm x 100 mm x 100 mm were casted and tested after 7 and 28 days of curing. The compressive strength results were presented in Table 4.

Table 4 showed that SCC with 5% of MK as cement replacement material had the highest compressive strength at 7 and 28 days of curing which were 50.6 MPa and 62.2 MPa respectively compared to other specimens. Sidek et al. [34] stated that the presence of MK in concrete can improve the strength of concrete. This is because MK has the ability to act as a filler, accelerate the cement hydration and pozzolanic reaction. On the other hand, it is observed that the SCC with addition of 0.5%

NF had the lowest compressive strength at the age of 7 and 28 days which were 41.1 MPa and 47.5 MPa. According to Spadea et al. [35] and Campello et al. [36], by adding NF in concrete more than 1%, it will create higher porosity or cavity which cause compressive strength of the concrete to decrease. Thus, it can be concluded that the usage of NF in the concrete more than 1% increased the porosity in the concrete matrix.

Table 4: Result of compressive strength test (MPa)

Mix Proportion	7 days age	28 days age
Controlled Mix	48.4	58.4
95%C 5%MK	50.6	62.2
100%C 0.5%NF	41.1	47.5
95%C 5%MK 0.5%NF	45.4	52

However, the porosity problem that came from the presence of NF in the concrete can be overcome by adding MK to the mix proportion. The result showed that the compressive strength of SCC with 5% MK and 0.5% increased at the age of 7 and 28 days compared to the SCC addition of 0.5% NF only which were 45.4 MPa and 52.0 MPa. Therefore, the combination of MK and NF in SCC can help to produce good quality SCC besides contributing in saving natural environment by recycling NF [37].

4.4. Split tensile strength

The results of splitting tensile strength for each mix were shown in Table 5. The test results were obtained from the compression machine by placing the 100 mm x 200 mm cylinder sample with 100mm diameter 200 mm height horizontally.

Table 5: Result of tensile strength test (MPa).

Mix Proportion	7 days age	7 days age
Controlled Mix	2.49	3.13
95%C 5%MK	2.79	3.36
100%C 0.5%NF	2.38	2.55
95%C 5%MK 0.5%NF	2.43	2.89

It was clearly shown in Table 5 that SCC with 95%C 5%MK had the highest tensile strength in 7 and 28 days which were 2.79 and 3.36 MPa compared to other samples. According to [38], usage of MK in concrete that caused pozzolanic reaction will increase the compressive and tensile of strength of the concrete.

Besides, SCC with addition of 0.5%NF had the lowest tensile strength for 7 and 28 days of curing which were 2.38 and 2.55 MPa. It was obvious that the SCC that contained NF had high tendency of high porosity that reduced its tensile strength [40]. However, the porosity problem caused by the NF can be overcome by adding MK to the mix proportion. This had be shown by the data of SCC with 95%C 5%MK 0.5%NF which had 2.43 and 2.89 MPa for 7 and 28 days of curing. The result shown that by combining the MK and NF, it would increase the tensile strength due to the ability of MK that act as filler to reduce the porosity in the concrete [34].

4.5. Flexural strength

Flexural strength tests were carried out on 100mm x100mm x 500mm prism samples after 28 days of curing. It was to identify the flexural strength of SCC containing metakaolin (MK) and nylon fiber (NF). As shown in Table 6, SCC with 5% of MK as cement replacement had the highest flexural strength which is 14.65 MPa whereas SCC with addition of 0.5% of NF had the lowest flexural strength which is 10.94 MPa.

Mix proportions containing NF like 100%C 0.5%NF and 95%C 5%MK 0.5%NF had lower flexural strength than the controlled mix because of NF's relative fiber matrix stiffness. Synthetic fibers like nylon and poly propylene have lower elastic modulus than other fibers [41]. To transfer stress due to loading efficiently, modulus of elasticity of cement matrix has to be much lower than the respective fiber [42]. In this context, elasticity modulus of NF is lower than cement matrix. Thus, NF is unlikely to improve the strength of SCC. This has been supported by [43], [44].

Table 6: Result of flexural strength test (MPa).

Mix Proportion	28 days age
Controlled Mix	12.2
95%C 5%MK	14.65
100%C 0.5%NF	10.94
95%C 5%MK 0.5%NF	11.35

Moreover, aspect ratio of fiber also influences the properties of SCC containing NF. According to [45], aspect ratio is calculated by dividing the length of fiber by its diameter. Typically, aspect ratio of fiber ranges from 30 to 150. As aspect ratio increase, the ultimate strength of concrete also increase but only up to 75. Beyond ratio of 75, the relative strength and toughness is reduced [42]. In this study, the aspect ratio used was 154 which already exceeded the typical range. Thus, addition of NF did not contribute strength to its flexural aspect and was supported by Hanif et al. [46].

Besides, orientation of fiber in concrete also affects its contribution towards strength of concrete. Fiber aligned parallel to the applied load offered more tensile strength and toughness than randomly distributed or perpendicular fibers [42]. Mahdi [47] had further discovered that fiber orientation with right angle to the direction of applied load had higher resistance towards fracture than randomly distributed fiber. Moreover, addition of fiber at large proportion may cause difficulty in matrix fluidity which then decreased the penetration ability of matrix between fiber and thus reduced fiber wetting before hardening of matrix, resulting in decrease in adhesion [48].

The strength of SCC improves after replacement of cement with MK was supported by research of Vujica and Skazlic [15]. Cement matrix homogeneity had increased due to addition of SCC. Furthermore, reaction MK with calcium hydroxide in hydrated cement would produce supplementary binder, resulting in increase of strength in SCC [49]. Presence of MK enables distinct densification in concrete which then leads to increment in strength and reduction in permeability [42]. Thus, 95%C 5%MK had higher strength than controlled mix and 95%C 5%MK 0.5%NF had higher strength than 100%C 0.5%NF.

5. Conclusion

Based on the fresh properties of SCC, each mix proportion were consistent in the context of slump flow, T500 and segregation resistance. This is because the classification of fresh SCC of each mix in each respective test were the same except for segregation resistance. It was observed that bleeding of SCC reduced when SCC containing MK, NF or both materials. This is because both MK and NF increase the water demand of SCC which then reduces the bleeding of fresh concrete. For mechanical properties of SCC, SCC containing 5% of MK achieved the highest compressive strength (62.2 MPa), split tensile strength (3.36 MPa) and flexural strength (14.65 MPa) than other mixes at the age of 28 days. MK improved cement matrix homogeneity by acting as a filler and causing pozzolonic reaction which then reduced permeability of SCC. Meanwhile, SCC with 0.5% NF had the lowest strength among the mix proportion due to low elasticity modulus, aspect ratio and orientation of NF besides the presence of porosity in concrete due to NF.

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