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Feasibility of using Metakaolin as a Self-Compacted Concrete Constituent Material

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***Abstract*— By minimizing the Portland cement (PC) content in concrete using supplementary cementitious material, reducing the CO_2 emission to the atmosphere is occurred. Metakaolin is one of these environmentally friendly materials. One of the most promising types of concrete is Self-compacted concrete (SCC). This research intends to investigate and assess the fresh and hardened properties of SCC containing Metakaolin by studying the impact of utilizing different cement and Metakaolin contents on concrete flow-ability, passing-ability and compressive and tensile strength. Fresh properties were investigated using new developed test named MSF Apparatus test and compared with the standard tests slump flow test and J-Ring test. The new developed test was highly accurate in SCC indication. Results showed adequate improvements by increasing Metakaolin content and cement content on the compressive and tensile strength. 15% Metakaolin content by the weight of cement as adding or replacement gives the best results.**

Keywords*— self-compacted, high strength, Metakaolin, environmental, flow-ability, fresh concrete, hardened concrete.

I. Introduction

Concrete has been developing in many ways to enhance the quality and properties of concrete. Self-compacting concrete (SCC) is one of the keys for the realization of durable concrete structures independent of the quality of construction work (Christianto H., 2004).

The manufacturing of High Strength Self Compacted Concrete that permanently meets requirements for workability and strength development places stricter requirements on the choice of materials than concrete of lower strength (Rashid et al., 2009). Numerous special ingredients are required in the production of high strength self-compacted concrete such as high-range water reducer (HRWR), supplementary cementing material (SCM), besides the basic materials used for ordinary (Sanjay et al., 2013).

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SCMs can be used for improving concrete performance in its fresh and hardened state. They are primarily used for improved workability, durability and strength. These materials could be produced as a by products from other processes or from natural materials such as Metakaolin (NRMCA, 2000).

Metakaolin, is a comparatively new material used in the concrete industry becomes one of the plenty ingredients in the production of an economical and environmentally friendly concrete of more than 40MPa. It is traditionally using Silica Fume to produce High Strength Concrete but when it is replaced by Metakaolin, the concrete properties and several features like strength, durability, water permeability, workability and flow-ability are improved (Shekarchi et al., 2010). The presence of MK has an immense effect on the hydration of Portland cement (PC). When Portland cement alone hydrates, typically 20-30% of the resulting paste mass is CH. However, when MK is introduced, it reacts rapidly with these newly forming CH compounds to produce supplementary calcium silicate hydrate (C-S-H) (Yusuff, 2005). Metakaolin substantially decreases the permeability of concrete, where the pores size in cement paste are reduced and many finer particles are transformed into discrete pores. Metakaolin improves compressive and flexural strengths. Also it leads to better shrinkage and crack control by reducing heat of hydration (Shekarchi et al., 2010). The utilization of this material is also environmentally friendly since it helps in reducing the CO2 emission to the atmosphere by the minimization of the Portland cement (PC) consumption (Rawat, 2012).

II. Research Significance

The present work will focus on developing self-compacted concrete mixtures using locally available materials. This experimental program was performed in two main phases to investigate the impact of using different cement and Metakaolin contents on the mechanical properties of self-compacting concrete samples and trying to achieve to High Strength Self-compacted concrete. The procedure of this research is divided into two main phases as follow:

A. *The First Phase*

This phase aims to determine the optimum water to binder ratios for different cement and Metakaolin contents to achieve the requirements of self-compacted concrete. Fresh concrete with different water to binder ratio was tested by using new developed test. MSF apparatus shown in Fig. 4 is the chosen name for the new test procedure.

B. *The Second Phase*

The second phase was based on testing 39 different mixtures from M1 to M39 which determined with the optimum water to binder ratios from the first stage. Fresh

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and hardened concrete properties were investigated in this phase. Slum flow test and J-ring test were carried out for all mixes to calibrate the determined water to binder ratios from the first phase. The Compressive strength and indirect tension tests were performed to investigate the properties of hardened self-compacted concrete of the chosen mixes

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III. Materials and Experimental Program

A. *Materials*

1) **Cement:** The used cement was ordinary Portland cement CEM I N52.5. Its chemical and physical characteristics satisfy the Egyptian Standard Specification (E.S.S. 4756-1/2009).

2) **Fine aggregate:** Natural and clean sand with a specific gravity 2.71 t/m^3 was used.

3) **Coarse aggregate:** Crushed Dolomite is used as coarse aggregate. The specific gravity and water absorption of the coarse aggregate are 2.65 t/m3 and 0.6% respectively. The grain size distribution curve for used aggregate is shown in Fig. 1.

4) **Super-plasticizer:** Sika Viscocrete 3425 a third generation polycarboxylate based super-plasticizer supplied by Sika Egypt company is the used super-plasticizer which meets the requirements of super-plasticizer according to ASTM-C-494, types G and F (ASTM C494, 2003). The used super-plasticizer has 1.08 Kg/lit density, 4.0 pH value and 40% solid content (by weight).

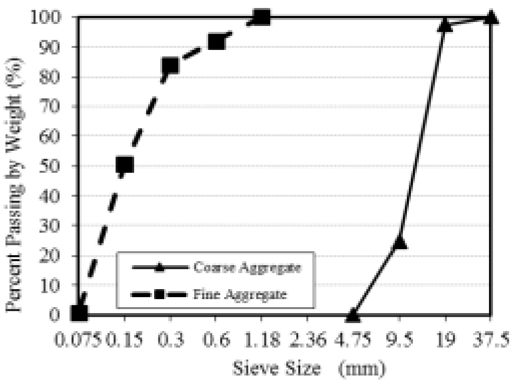

Figure 1. The Grain Size Distribution Curve for Used Aggregate

5) **Metakaolin (MK):** Metakaolin sample is shown in Fig. 2. The used MK was produced by Nourmetec for building and Refractories Company. The microstructural composition of the used Metakaolin was investigated by means of powder X-ray diffraction analysis (XRD) Fig. 3. The chemical components analysis was shown in Table 1.

Figure 2. Calcined Kaolin (Metakolin)

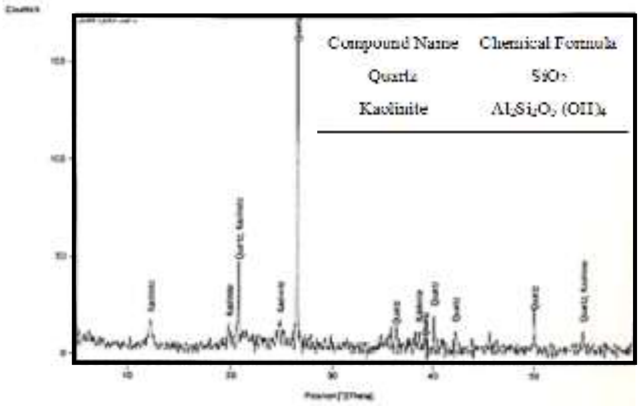

Figure 3. X-ray diffraction of Metakaolin

TABLE I. THE CHEMICAL COMPONENTS ANALYSIS RESULT OF THE USED METAKAOLIN

Chemical Composition	Average (%)
SiO_2	53.90
Al_2O_3	35.90
Fe_2O_3	1.57
CaO	0.95
MgO	0.17
Na_2O+K_2O	0.16
L.O.I	3.95

B. *Mixtures Proportions*

Seven contents of Metakaolin were used as a percentage from 0.0% to 30% as adding and replacement of the mixture cement content (MK/C) to investigate its effect on the self-compacting concrete. Super-plasticizer is used as 1.0% percentage by weight of binder content. Cement content was chosen as 450, 550 and 650 kg/m^3. Sand and crushed dolomite content was the same for all the mixtures in this research.

C. *Concrete Samples*

Specimens in this research cast to explore the main properties of the different 39 concrete mixes, which are the compressive strength and the indirect tensile strength. Standard cubes of dimensions 100x100x100 mm were used to measure the compressive strength and cylinders of 100 mm diameter and 200 mm height were used to measure the indirect tensile strength.

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D. ***Testing Procedures and Equipment***

1) **Fresh (SCC)**

Fresh concrete tests are necessary in this study. SCC is defined by its behaviour when it is in the fresh state, and it is determined whether concrete meets certain requirements. The workability tests which are mainly recommended by the British standards (BS EN 206-9, 2010) are the slump flow test for flowing ability and J-ring tests for passing ability. In this section, new developed test (MSF apparatus) was described.

A) **MSF Apparatus Test**

MSF Apparatus test is the chosen name for the new test procedure and the dimension of the used apparatus is shown in Fig. 4, the MSF Apparatus test is used to appraise the deformability of SCC in the absence of obstacles. This test gives rapid indication about two different aspects; the filling ability and the segregation resistance in this test can be detected visually. The main advantages of the MSF Apparatus test is that it need small volume of fresh concrete about (1.0 litre) and the required space for the test is also small (need a plate of (400x400 mm) compared to that of the ordinary slump flow test that need (about 9.0 Litters).

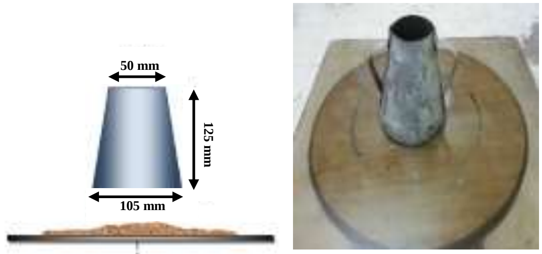

Figure 4. MSF Apparatus test cone dimensions

- **Test Apparatus**

- Mould: Steel cone mould with diameters of 50 mm at bottom and 105 mm at top with 125 mm height.
- Base Plate: non-absorbent, smooth, and rigid and have dimensions of 400 x 400 mm with plotted circle of 200 mm diameter in the centre.

- **Test Procedure and Calculations**

The procedure and calculations of MSF Apparatus test is the same as slump flow test which is recommended by the British standard (BS EN 206-9, 2010) except that the measured time needed for SCC to reach 500mm diameter is replaced by that measured to reach 200 mm flow (T_{200}).

- **Acceptance Limits**

- Achieving a large diameter with no segregation indicates a good deformability.
- T200 'the time needed for SCC to reach a diameter of 200 mm' should be between 5 to 10 seconds.
- The average slump flow diameter should be between 250 to 280 mm.
- Segregation can be detected by visually inspecting a ring of cement paste/mortar in the edge of flow, and /or ensuring that no coarse aggregates has lifted in the centre of flow.
- This limits are valid for aggregates with maximum nominal size not more than 12.50 mm.

2) **Hardened (SCC)**

The hardened concrete tests which are recommended by Egyptian Standard Specification (E.S.S. 4756-1/2009) are compression test and indirect tension test. Compression test was carried out to determine the compressive strength of specimens of concrete cubes. Indirect tension test (splitting method) was performed to determine the tensile strength of concrete mixes using cylindrical specimens.

IV. Test Results and Discussions

The test results of fresh and hardened concrete are analysed to investigate the effect of different contents of cement as well as the effect of adding and replacing Metakaolin contents on the self-compacted concrete. The results of the performed experimental work are divided in two phases.

A. ***Phase One:***

In this phase different cement and Metakaolin (MK) contents with different water to binder ratios (W/B) and 1.0% super-plasticizer content were tested using MSF Apparatus test to determine the acceptable water to binder ratios that meet the requirements of the self-compacted concrete.

Thirty nine mixes were chosen as an acceptable mixes that satisfied the requirements of self-compacted concrete and with minimum water to binder ratio. Table 2 show the selected mixes, MSF Apparatus test results and comparable slump flow d J-Ring test results. Fig. 5(a) shows an accepted sample, while Fig. 5(b) shows refused samples using MSF Apparatus test.

(5-a) Good flow-ability (Accepted sample)

(b-1) Segregation

(b-2) Low Flow-ability

(b-3) Unflowable

(5-b) Refused samples

Figure 5. MSF Apparatus test accepted and refused sample

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TABLE II. FRESH AND HARDNED CONCRETE TEST RESULTS

Mix No.	C (Kg/m^3)	W/B (%)	(MK/C) (%)	MSF Apparatus test		Slump flow test		J-Ring test		Compressive strength (MPa)		Tensile strength (MPa)	
				Time (Sec.)	D_{ave} (Cm)	Time (Sec.)	D_{ave} (Cm)	Time (Sec.)	Dave (Cm)	7 days	28 days	7 days	28 days
M1		0.39	0	9.5	26	4.5	70	4.95	69	38.43	44.79	3.65	4.22
M2		0.38	5	7.62	27	3.98	73	4.23	72.5	39.17	45.91	3.88	4.61
M3		0.38	10	7.41	26.5	4.02	74	4.65	73.5	42.41	47.02	4.04	5.16
M4		0.38	15	7.2	26.5	4.08	73.5	4.22	72	43.85	48.74	4.36	5.49
M5		0.38	20	8.21	26.5	4.44	68	4.76	66	41.92	47.79	3.96	5.11
M6		0.38	25	8.9	25	4.75	69	5.01	67.5	39.99	43.99	3.61	4.34
M7	450	0.38	30	7.81	26.5	3.51	75	4.12	73.5	32.00	35.20	3.12	3.83
M8		0.39	-5	9.1	26.5	4.45	72	4.97	70.5	34.02	37.52	3.54	3.98
M9		0.43	-10	7.56	27.5	4.73	73	5.08	71	36.48	39.41	3.66	4.18
M10		0.43	-15	7.41	27.5	4.42	74	4.95	72.5	41.35	46.32	3.88	4.43
M11		0.43	-20	7.82	26.5	3.24	75	3.97	74	33.17	37.79	2.85	3.36
M12		0.43	-25	9.12	25.5	4.63	71	4.87	69.5	25.47	31.51	2.65	3.27
M13		0.43	-30	6.64	25.5	4.23	70.5	4.93	69	23.11	30.26	2.55	3.19
M14		0.33	0	8.25	28	3.14	74	3.98	73	47.62	51.28	5.09	6.25
M15		0.33	5	7.53	26.75	4.66	69	4.74	67.5	51.77	59.61	5.87	7.01
M16		0.32	10	7.54	26.25	4.51	70	4.96	68.5	56.93	67.94	6.21	7.77
M17		0.32	15	7.24	27.5	4.63	69	5.02	67.5	58.86	73.74	7.01	8.10
M18		0.32	20	9.78	27	4.21	67	4.81	66.5	54.17	62.58	6.48	7.45
M19		0.32	25	7.67	26	4.12	71	3.97	69	50.86	59.45	5.72	6.91
M20	550	0.33	30	6.67	26.5	4.35	69	4.93	67	40.77	48.12	5.10	6.42
M21		0.33	-5	6.9	26	4.47	68.5	5.01	67	44.15	49.29	4.96	6.70
M22		0.36	-10	6.2	25.75	4.20	67.5	4.64	66	45.71	50.46	5.04	6.95
M23		0.36	-15	5.9	26.25	3.75	72.5	4.25	73	49.13	54.20	5.22	7.07
M24		0.36	-20	6.3	25.5	4.52	69.5	4.90	69	40.58	47.50	4.59	6.48
M25		0.36	-25	7.31	26.75	3.98	71.5	4.20	70	37.75	42.44	4.00	5.90
M26		0.36	-30	7.86	25	3.86	69.5	4.68	68.5	36.15	40.97	3.84	5.45
M27		0.3	0	6.57	25.5	4.45	70	5.3	71	50.00	58.80	5.86	6.56
M28		0.3	5	5.89	27.5	4.61	70	4.93	68.5	52.85	67.13	6.23	7.24
M29		0.29	10	8.65	26.5	4.50	71	4.89	70	58.78	74.47	6.70	8.02
M30		0.29	15	9.65	26.5	4.80	72	5.1	70	61.95	78.15	7.48	8.36
M31		0.29	20	6.97	25.75	4.12	70.5	4.25	69	60.38	68.64	6.76	7.56
M32		0.29	25	6.35	27.5	4.87	69	5.04	68	55.96	65.20	6.21	7.15
M33	650	0.29	30	8.32	27	4.53	71	4.80	69.5	51.25	55.27	5.83	6.82
M34		0.3	-5	5.64	27	4.70	71	4.93	70	46.30	57.93	5.68	6.91
M35		0.33	-10	7.51	26.5	4.21	70	4.5	68.5	47.25	58.15	5.86	7.22
M36		0.33	-15	7.63	27.5	4.57	69	4.69	68	51.42	62.05	6.05	7.50
M37		0.33	-20	6.53	25.5	4.24	71	4.93	68.5	43.75	54.51	5.43	6.69
M38		0.33	-25	7.31	26	4.88	70.5	5.20	69	39.29	49.12	4.57	6.34
M39		0.33	-30	6.39	27.5	4.75	71	4.91	70	38.50	46.14	4.22	6.13

*Fine aggregate and coarse aggregate contents were fixed to 762 kg/m^3, while super-plasticizer content was chosen as 1.0% of binder content

B. *Phase Two:*

The hardened properties of the self-compacted concrete which were taken into consideration in phase two in this research were the compressive strength at age of 7 and 28 days and the indirect tensile strength at age of 7 and 28 days of the self-compacted concrete. In the second phase fresh and hardened properties of self-compacted concrete were investigated and the tests results are presented and discussed.

1) **Mechanical Properties Results and Discussion:**

The compressive strength test results are shown in Table 2 and Figs. 6 to 9 and the indirect tensile strength test results are shown in Table 2 and Figs. 10 to 13. The results show that there is a great positive effect of increasing Metakaolin content on both the compressive and the tensile strength of SCC at 7 and 28 days regardless cement content.

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By adding MK/C of 5 to 30 percentage, it was observed that increasing Metakaolin content affect the compressive strength and tensile strength which tended to increase and then decreased. At the age of 7 days and 28 days the maximum increase was at 15% MK/C percentage.

At the age of 7 days, the compressive strength increased by about 14.12%, 23.60% and 23.90% at 450, 550 and 650 Kg/m^3 cement contents respectively while the tensile strength increased by about 19.45%, 37.72% and 27.65% at 450, 550 and 650 Kg/m^3 cement contents respectively with adding (MK/C%) compared to samples without MK. At the age of 28 days, the compressive strength increased by about 8.82%, 43.80% and 32.90% at 450, 550 and 650 Kg/m^3 cement contents respectively while the tensile strength increased by about 30.09%, 29.60% and 27.44% at 450, 550 and 650 Kg/m^3 cement contents respectively with adding Metakaolin to cement percentages (MK/C%) compared to samples without MK.

Using MK as a replacement by weight of cement of 5 to 30 percentages, the compressive strength and the tensile strength first decreased and then increased. At the age of 7 days and 28 days the maximum increase was at 15% MK/C percentage. The compressive strength increased by about 7.61%, 3.17% and 2.83% at 450, 550 and 650 Kg/m^3 cement contents respectively at the age of 7 days while the maximum tensile strength increase was about 6.30%, 2.55% and 3.24% at 450, 550 and 650 Kg/m^3 cement contents respectively. At the age of 28 days, the compressive strength increased by about 3.41%, 5.70% and 5.53% at 450, 550 and 650 Kg/m^3 cement contents respectively compared to samples without MK. The maximum tensile strength increase was at 15% MK/C percentage. The tensile strength was increased by about 4.98%, 13.12% and 14.33% at 450, 550 and 650 Kg/m^3 cement contents respectively compared to samples without MK with respect to samples with replacing (MK/C%).

Increasing the cement content increases the compressive strength and also the tensile strength of SCC samples' at age of 7 and 28 days. For samples with adding MK/C percentage the compressive strength at 7 days increased with average of 29.80% at 550Kg/m^3 and by about 41.30% at 650 Kg/m^3 cement content. The tensile strength at 7 days increased with average of 55.90% at 550Kg/m^3 and by about 69.80% at 650 Kg/m^3 cement content compared to cement content of 450 kg/m^3. At 28 days the compressive strength increased with the increasing of cement content by with average of 34.70% at 550Kg/m^3 and by about 49.30% at 650 Kg/m^3 cement content, while the tensile strength increased with the increasing of cement content by about 53.0% at 550Kg/m^3 and by about 58.80% at 650 Kg/m^3 cement content compared to cement content of 450 kg/m^3.

For samples with replacing MK/C percentage the compressive strength at 7 days increased with average of 33.50% at 550Kg/m^3 and by about 40.45% at 650 Kg/m^3 cement content. The tensile strength at 7 days increased by about 45.80% at 550Kg/m^3 and by about 67.50% at 650 Kg/m^3 cement content compared to cement content of 450 kg/m^3. At 28 days the compressive strength increased with the increasing of cement content by about 28.70% at 550Kg/m^3 and by about 48.10% at 650 Kg/m^3 cement content. While the tensile strength increased with the increasing of cement content by about 73.10% at 550Kg/m^3 and by about 83.50% at 650 Kg/m^3 cement content compared to cement content of 450 kg/m^3.

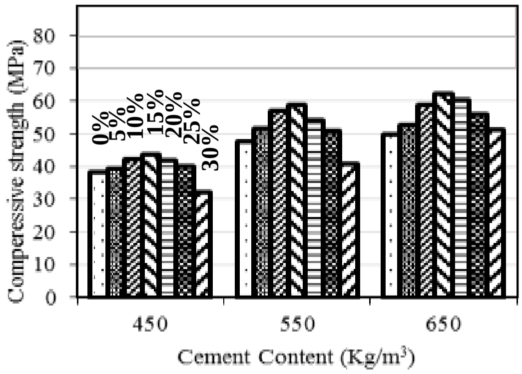

Figure 6. Effect of Cement content with adding Metakaolin contents (MK%) on 7 days compressive strength

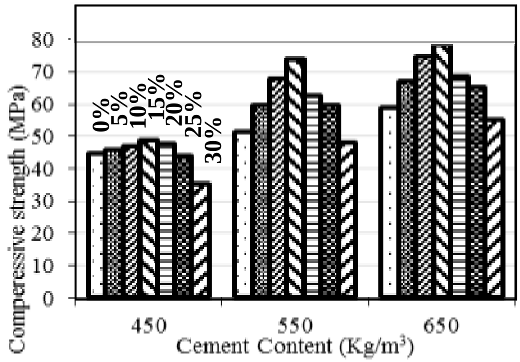

Figure 7. Effect of Cement content with adding Metakaolin contents (MK%) on 28 days compressive strength

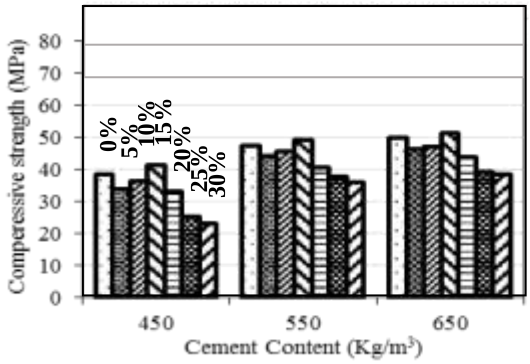

Figure 8. Effect of Cement content with replacing Metakaolin contents (MK%) on 7 days compressive strength

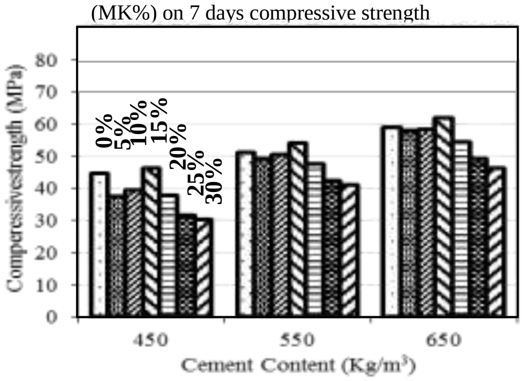

Figure 9. Effect of Cement content with replacing Metakaolin contents (MK%) on 28 days compressive strength

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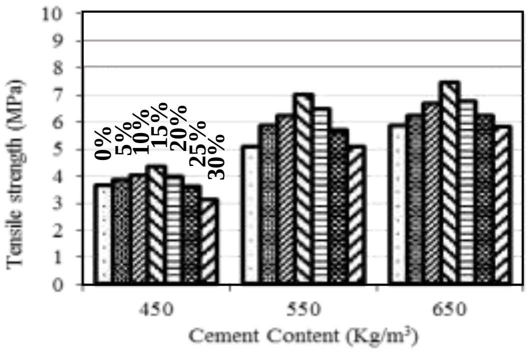

Figure 10. Effect of Cement content with adding Metakaolin contents (MK%) on 7 days tensile strength

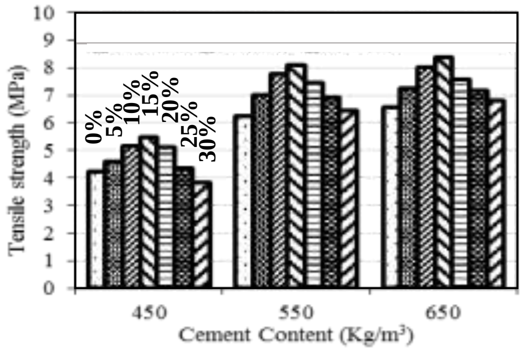

Figure 11. Effect of Cement content with adding Metakaolin contents (MK%) on 28 days tensile strength

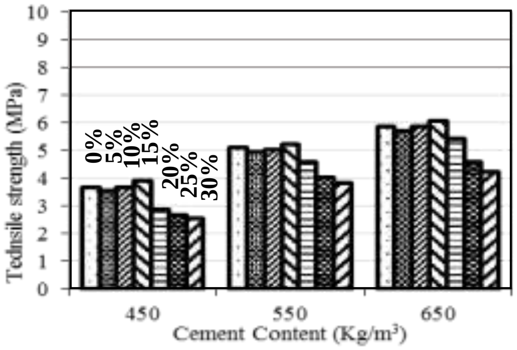

Figure 12. Effect of Cement content with replacing Metakaolin contents (MK%) on 7 days tensile strength

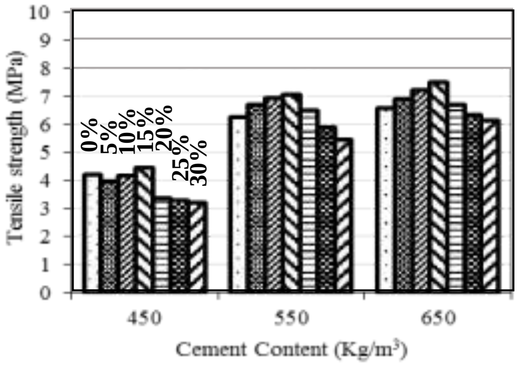

Figure 13. Effect of Cement content with replacing Metakaolin contents (MK%) on 28 days tensile strength

From the previous results it could be indicated that that adding or replacing 15% Metakaolin to cement percentage was the best percentage in the 7 and 28 days compressive and tensile strength which were coincident with the results of (Rawat, 2012; Sabir et al., 2001).

V. Conclusions

Based on the results obtained from the current research, the following main conclusions can be summarized:

- Self-compacted concrete can be achieved using Metakaolin as a cementitous material.
- The MSF Apparatus test is a new developed test that need small volume of fresh concrete about (1.0 litre) and required small space for the test compared to that of the ordinary slump flow test that need.
- The MSF Apparatus test results is highly accurate comparing with indicated results from the slump flow test and J-Ring test.
- There is a great positive effect of increasing Metakaolin content on the compressive and tensile strength at 7 and 28 days age for self-compacted concrete.
- Using Metakaolin content from 5 to 15% by weight of cement as adding or replacement gives higher strength than samples without Metakaolin content. The maximum strength could be obtained by using 15% of Metakaolin as adding or replacing percentage by weight of cement.
- The increasing in cement content has a positive effect on the compressive strength and tensile strength at 7 and 28 days of self-compacted concrete ages without considering the Metakaolin content.

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