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# *Production of High Performance Mortar Containing Metakaoline and Silica Fume*

Abdalaziz Saad Shawkat[1], Eethar Thanon Dawood[2]

[1] MSc student, Building and Construction Eng. Technical College of Mosul, Northern Technical College of Mosul, Northern Technical University.

[2] Associate Prof., PhD , Building and Construction Eng. Technical College of Mosul, Northern Technical College of Mosul, Northern Technical University



**Abstract – The utilization of Pozzolanic materials is fundamental in producing low cost construction materials for utilization in growing nations. This paper elaborates on the effect of Silica fume (SF) and Metakaolin (MK) mixture as a partial replacement of cement in mortar. The using of the high range water reducer (superplasticizer) gives higher quality than plane mixes. (SF) is a ''very fine noncrystalline silica produced in electric arc furnaces as a by-product of production of elemental silicon or alloys containing silicon''. The fundamental physical effect of (SF) in concrete is that of filler, because of its fineness can fill the voids between (OPC) particles in the same way that fine aggregate fills the voids between coarse aggregates. This research shows the result of an experimental program carried out to find the suitability of (SF) and (MK) combination to produce High Performance Mortar (HPM). The optimal doses of (SF) and (MK) in combination were found to be 9% and 11% (by weight) respectively, when used as partial replacement of (OPC).**

**Keywords – High Performance Mortar, Silica Fume, Metakaolin, Supplementary Cementitious Materials.**

## I. INTRODUCTION

Concrete is the worldwide used and adjustable building material which has relatively high compressive strength. (OPC) is the main ingredient of concrete as it acts as a binding material to obtain a hardened matrix. The widespread production of cement lead to emission of carbon dioxide, which procure global warming by imposing environmental issues. The solution of this global issue is to use the mineral admixtures as a substitution of OPC. Most of the modern concrete mixes were enhanced in their properties by using mineral admixtures, which make the microstructure more dense and decreases $CA(OH)_2$ concentration by utilizing it in the pozzolanic reaction. By this enhancement in microstructure there will be an improvement in durability and service-life properties and growth in mechanical properties. The fundamental physical effect of (SF) in concrete is that of filler, because of its fineness can fill the voids between (OPC) particles in the same way that fine aggregate fills the voids between coarse aggregates. The chemical effect of (SF) in concrete demonstrated by the reaction between amorphous silicon in (SF) and Ca(OH)2 in (OPC) to form an additional binding material called calcium silicate hydrate (C-S-H) which is very similar to the (C-S-H) obtained from Hydrated (OPC). SF is very effective SCM which is efficient in improving strength characteristics to higher values. SF enhance mechanical characteristics as well as durability of concrete. Strengths shows enhancement with respect to control mortar at (6 - 9) % substitution of SF, while high proportions of SF do not make further improvement in strength. The amount of High Range Water Reducer (HRWR) has an effect on concrete strength. HRWR can affect the concrete strength even at constant water-cement ratio. If the quantity of HRWR is altered by the percentage replacement of SCMs, then the alterations in strength of concrete will take place because of change in HRWR[1-5].

(MK) is also one of such waste/ non - conventional material, gained by calcination of pure kaolinitic clay at a temperature of between 650 and 850 °C, followed by grinding process The resulting material exhibits high pozzolana activity.

MK is a supplementary cementitious material which can provide many specific features. MK is available in many different varieties and qualities. The purity (or free lime content) will govern the binding capacity. MK is a valuable admixture for concrete or cement applications. The effective level of replacement usually within (8% - 20%) (by weight). Such a concrete exhibits favorable engineering properties. The pozzolanic reaction starts soon and continues between 7 to 28 days. For the preliminary investigation, SF, MK and cement were subjected to physical and chemical analyses to determine whether they are in compliance with the specifications. The experimental program was designed to investigate SF and MK as a partial replacement of the OPC, it was done at 6%, 9%, 12% and 15%. The specimen was cast with mortar with different replacement levels of MK[6-8].

Both the SF and MK are useful SCMs. In the present work, the results of a study carried out to investigate the effects of these two materials within two phases:-

1. Individually Investigation: to observe the effects of each material on strength, absorption and void ratio of mortar. The referral mortar was made using (1 : 2.2 / 0.38 HRWR 1%) by weight mix proportion and the other mixes were prepared by partial replacing of OPC with SF and MK. The substitution levels were 6%, 9%, 12% and 15% (by weight) for both materials and the HRWR varied uniformly with the alteration of substitution levels so as to keep the flow within the range (105 % - 110 %).
2. Combined Investigation: to observe the combined effect for both materials on strength, absorption and void ratio of mortar. The referral mortar was made using (1 : 2.2 / 0.38 HRWR 1%) by weight mix proportion and the other mixes were prepared by totally partial replacing of OPC with 20%. The latter Percentage is Shared within different portions (11:9, 9:11, 14:6, 12:8, 10:10) between SF and MK respectively. The HRWR varied uniformly with the alteration of substitution levels so as to keep the flow within the range (105 % - 110 %).

## II. Problem Statement

The benefits of Supplementary cementitious materials (SCM) as partial replacement of ordinary portland cement (OPC) are well proven. Frugal by decreasing cement content and environmental advantages by decreasing CO2 emission are well known. By addition of some (SCM), the various properties of concrete like durability, strength, resistance to cracks and absorption can be improved.

## III. Objectives Of The Study

The overall objectives of this work are to prepare hydraulic mortar for each level of OPC substitution and test their mechanical properties. Besides, the comparison between the referral mortar and the mortar of each level of substitution.

The measurable objectives are to:

1- Determine whether the SCMs are in compliance with the specifications.

2- Make a comparative evaluation of various levels of individually substitution mortar with each of SF and MK based on their hardened properties such as; compressive strength, flexural strength, absorption and void ratio.

3- Determine whether the two materials (SF & MK) are suitable to combine together within the mix.

4- Investigate the optimal rate of substitution of both materials in the combined state.

## IV. Materials

1. Cement: Locally available cement is used to produce mortar. Such cement was obtained from Delta cement factory (Sulaimaniyah governorate of Iraq).The physical Properties are shown in Table 1 Besides, The chemical compositions are shown in Table 2. both chemical and physical characteristics are in compliance with Iraqi Standard Specification "IQS: 5/1984".

Table 1: Physical Properties of Cement

| Physical properties | Results | Limits of IQS: 5/1984 |
|---|---|---|
| Initial setting time (minute) | 100 | $\geq$ 45 minute |
| Final setting time (minute) | 320 | $\leq$ 600 minute |
| Fineness (Blaine $m^2$/ kg) | 300 | $\geq$ 230 ($m^2$/ kg) |
| Soundness by Autoclave Method (%) | 0.02 | Not more than 0.8 |
| Compressive strength (MPa) | | |
| 3 days | 21 | $\geq$ 15 |
| 7 days | 27 | $\geq$ 23 |

Table 2: Chemical Composition of Cement

| Composition | Abbreviation | Percentage by weight | Limits of IQS: 5/1984 |
|---|---|---|---|
| Lime | $CaO$ | 61 | - |
| Silica | $SiO_2$ | 19.84 | - |
| Alumina | $Al_2O_3$ | 5.08 | - |
| Iron Oxide | $Fe_2O_3$ | 4.8 | - |
| Sulphate | $SO_3$ | 2.49 | $\leq$ 2.8 |
| Potash | $K_2O$ | 0.1 | |
| Soda | $Na_2O$ | 0.3 | |
| Equivalent $Na_2O$ | $Na_2O+0.658K_2O$ | 0.36 | $\leq$ 0.6% |
| Magnesia | $MgO$ | 2.48 | $\leq$ 5.0 % |
| Loss on ignition | L.O.I. | 3.8 | $\leq$ 4.0 % |
| Insoluble Residue | I.R. | 0.40 | $\leq$ 1.5 % |
| Lime saturation factor | L.S.F | 0.94 | |
| Main Compounds (Bogue′s equations) | | | |
| Tri calcium Silicate | $C_3S$ | 49.45 | - |
| Di calcium Silicate | $C_2S$ | 19.57 | - |
| Tri calcium Aluminate | $C_3A$ | 5.34 | - |
| Tetra calcium Aluminate –Ferrite | $C_4AF$ | 14.61 | - |

2. **Silica Fume:** Silica fume (Mega Add Conmix) was used as a partial replacement of cement, the material properties are shown in the Table3.

Table 3: Properties of Silica Fume

| Form | Agglomerated |
|---|---|
| Particles Color/ Appearance | Grey |
| Specific Gravity | 2.20 |
| Size of particles | 0.1 μ |
| Dosage | 2 - 10% by weight of cement |
| Chloride content | Nil |
| Strength Activity Index | 111% |
| Water requirement | 100% |
| Lime (CaO) | 1.0% |
| Silica ($SiO_2$) | 92.5% |
| Alumina ($Al_2O_3$) | 1.2% |
| Iron Oxide ($Fe_2O_3$) | 2.0% |
| Loss of Ignition | 3.4% |

3. ***Metakaolin:*** natural white kaolinite clay was brought from refractories plant located in erbil city .Metakaolin was activated by calcination of pure kaolinitic clay at a temperature of between 650 and 850 °C for 1 hour, followed by grinding process. Properties of Metakaolin are shown in table 4

Table 4. Properties of Metakaolin

| Chemical composition | % |
|---|---|
| Silica ($SiO_2$) | 54.3 |
| Alumina $Al_2O_3$ | 38.3 |
| Calcium oxide CaO | 0.39 |
| Ferric oxide Calcium oxide ($Fe_2O_3$) | 4.28 |
| Magnesium oxide (MgO) | 0.08 |
| Potassium oxide ($K_2O$) | 0.50 |
| Sulphuric anhydride ($SO_4$) | 0.22 |
| LOI | 0.68 |
| Specific gravity | 2.5 |
| Physical Form | Fine Powder |
| Colour | Off white |
| | |

4. **High Range Water Reducer (Superplasticizer):-** superplasticizer from conmix was used to establish the desired workability of the mixes this superplasticizer is conformed to ASTM C494 type F. It's properties are shown in table 5.

Table 5 Properties of HRWR

| | |
|---|---|
| **Appearance** | **Liquid** |
| **Color** | **Brownish** |
| **Specific Gravity** | **1.01** |
| **Chloride Content** | **Nil** |
| **Compatibility with Cement** | **All Types of Portland Cement** |
| **Shelf Life** | **Up to 1 Year** |

5. **Sand:-** The natural sand used as fine aggregate was supplied from kalak region. The specific gravity is 2.6. The grading limits are given in the Figure 1 below.

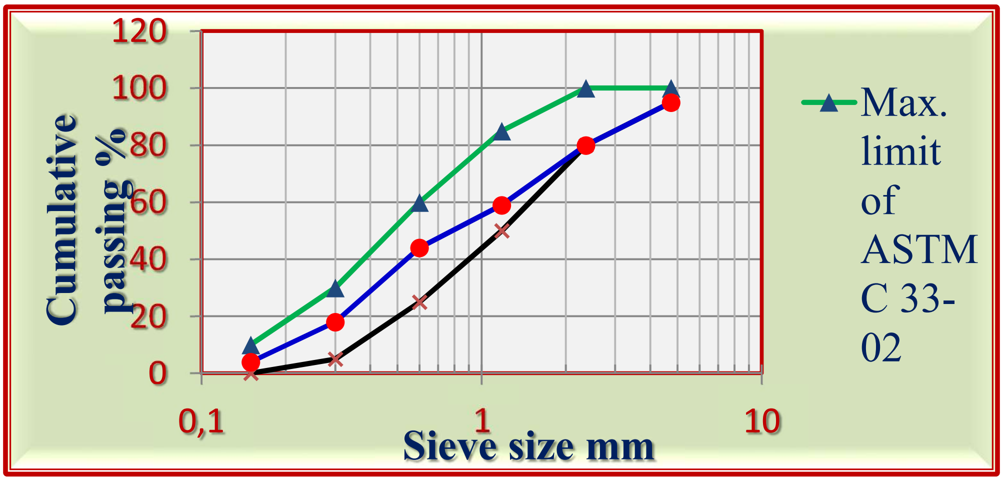


Figure 1. The grading limits.

6. **Tap Water:- :** Normal tap water was used in this study for mixing and normal curing.

## V. Mix Proportion

***Phase I-***

A total of ten mortar mixes (five mixes for each material individually) were prepared using water-binder (OPC+SCMs) in a ratio of 0.38 and the mineral admixtures (SF & MK) was used in the order of (6%, 9%, 12% &15%) as a substitution of cement. The amount of sand and HRWR were kept constant. The amount free water varied from (0.38 -0.42) % by weight of binder content to maintain flowability for all the mixes as shown in the tables 6 and 7.

Table 6 mix proportion for Silica fume mortars

| Index | Cement ($Kg/m^3$) | SF ($Kg/m^3$) | Sand ($Kg/m^3$) | HRWR % by weight of binder | Water Content ($L/m^3$) |
|---|---|---|---|---|---|
| $SF_0$ | 636 | 0 | 1400 | 1 | 242 |

| | | | | | |
|---|---|---|---|---|---|
| $SF_1$ | 598 | 38 | 1400 | 1 | 252 |
| $SF_2$ | 579 | 57 | 1400 | 1 | 257 |
| $SF_3$ | 560 | 76 | 1400 | 1 | 262 |
| $SF_4$ | 541 | 95 | 1400 | 1 | 267 |
| Flowability for each mix was within the range (105-115) % | | | | | |

Table 7 mix proportion for Metakaolin mortars

| Index | Cement (Kg/m$^3$) | MK (Kg/m$^3$) | Sand (Kg/m$^3$) | HRWR % by weight of binder | Water Content (L/m$^3$) |
|---|---|---|---|---|---|
| $MK_0$ | 636 | 0 | 1400 | 1 | 242 |
| $MK_1$ | 598 | 38 | 1400 | 1 | 247 |
| $MK_2$ | 579 | 57 | 1400 | 1 | 252 |
| $MK_3$ | 560 | 76 | 1400 | 1 | 250 |
| $MK_4$ | 541 | 95 | 1400 | 1 | 247 |
| Flowability for each mix was within the range (105-115) % | | | | | |

***Phase II-***

A total of six mortar mixes were prepared using water-binder (OPC+SCMs) in a ratio of 0.38 and the total replacement by mineral admixtures (SF & MK) was used in the order of 20% The latter Percentage is Shared within different portions (11:9, 9:11, 14:6, 12:8, 10:10) % between SF and MK respectively. The amount of cement, sand and free water were kept constant. The amount HRWR varied from (1 - 1.6) % by weight of binder content to maintain flowability for all the mixes as shown in table 8

Table 8 mix proportion for combined MK and SF mortars

| Index | Cement (Kg/m$^3$) | MK (Kg/m$^3$) | SF (Kg/m$^3$) | Sand (Kg/m$^3$) | HRWR % by weight of binder | Water Content (L/m$^3$) |
|---|---|---|---|---|---|---|
| $MS_0$ | 636 | 0 | 0 | 1400 | 1 | 242 |
| $MS_1$ | 504 | 59.4 | 72.6 | 1400 | 1.3 | 242 |
| $MS_2$ | 504 | 72.6 | 59.4 | 1400 | 1.2 | 242 |
| $MS_3$ | 504 | 39.6 | 92.4 | 1400 | 1.5 | 242 |
| $MS_4$ | 504 | 52.8 | 79.2 | 1400 | 1.6 | 242 |
| $MS_5$ | 504 | 66 | 66 | 1400 | 1.4 | 242 |
| Flowability for each mix was within the range (105-115) % | | | | | | |

## VI. Test Method

Three cube 50×50×50 mm samples were used for each mix to test the compressive strength at various ages 7 and 28 days according to ASTM C109. The flow test for mixes was performed according to ASTM C230 with a designed flow of (105-115) %. The cube specimens were left in the molds for 24 hours at 20 °C after casting. After demolding, the specimens were kept in plain water until the time of the test. The compressive strength test was performed directly after the absorption test according to ASTM C642. Besides, three 40×40×160 mm prismatic steel molds were used to prepare the specimens for the flexural strength test according to ASTM C348

## VII. Test Results And Discussion

The test results for HPM mixes prepared by metakaoline (MK) are shown in Table 9. It can be seen from this Table that the inclusion of metakaoline gives good ehancements in compressive, flexural strengths and absorption of HPM. The best improvements have been obtained due to 12% of MK for different percentages replacement. Thus, the compressive strength of HPM has been increased from 70.145 MPa to 75.864 MPa.Continously, the flexural strength of HPM has been increased from 6.672 MPa to 7.424 MPa.Also, the absorption of HPM has been decreased from 7.634% to 7.096% for such replacement of MK.

The test results for HPM mixes prepared by silica fume (SF) are shown in Table 10. It can be seen from this Table that the inclusion of SF gives good improvements in compressive, flexural strengths and absorption of HPM. The best improvements have been obtained due to 6% of SF for different percentages replacement. Thus, the compressive strength of HPM has been increased from 70.145 MPa to 76.588 MPa.Besides, the flexural strength of HPM has been increased from 6.672 MPa to 7.334 MPa.Also, the absorption of HPM has been decreased from 7.634% to 7.044% for such replacement of SF.

The test results for HPM mixes prepared by the combination of silica fume (SF) and Metakaoline are shown in Table 11. It can be seen from this Table that the inclusion of 11% MK + 9% SF gives the best improvements in compressive, flexural strengths and absorption of HPM.

Thus, the compressive strength of HPM has been increased from 70.145 MPa to 80.104 MPa.Continously, the flexural strength of HPM has been increased from 6.672 MPa to 7.482 MPa.Also, the absorption of HPM has been decreased from 7.634% to 6.884% for such replacements of MK and SF.

Table 9 Tests Results for Metakaolin mortars

| Index | MK % binder | Compressive Strength @ 7 days (Mpa) | Compressive Strength @ 28 days (Mpa) | Flexural Strength @ 28 days (Mpa) | Absorption% |
|---|---|---|---|---|---|
| $MK_0$ | 0% | 45.132 | 70.145 | 6.672 | 7.634 |
| $MK_1$ | 6% | 46.974 | 73.037 | 6.966 | 7.261 |
| $MK_2$ | 9% | 48.627 | 74.325 | 7.142 | 7.112 |
| $MK_3$ | 12% | 50.815 | 75.864 | 7.424 | 7.096 |
| $MK_4$ | 15% | 47.156 | 69.731 | 6.447 | 7.728 |
| Flowability for each mix was within the range (105-115) % | | | | | |

Table 10 Tests Results for Silica Fume mortars

| Index | SF % binder | Compressive Strength @ 7 days (Mpa) | Compressive Strength @ 28 days (Mpa) | Flexural Strength @ 28 days (Mpa) | Absorption% |
|---|---|---|---|---|---|
| $SF_0$ | 0% | 45.132 | 70.145 | 6.672 | 7.634 |
| $SF_1$ | 6% | 51.547 | 76.588 | 7.334 | 7.044 |
| $SF_2$ | 9% | 49.631 | 73.136 | 7.046 | 7.367 |
| $SF_3$ | 12% | 48.413 | 70.562 | 6.723 | 7.611 |
| $SF_4$ | 15% | 48.132 | 68.367 | 6.383 | 7.762 |
| Flowability for each mix was within the range (105-115) % | | | | | |

Table 11 Tests Results for combined SF and MK mortars

| Index | MK % binder | SF %binder | Compressive Strength @ 7 days (Mpa) | Compressive Strength @ 28 days (Mpa) | Flexural Strength @ 28 days (Mpa) | Absorption% |
|---|---|---|---|---|---|---|
| $MS_0$ | 0% | 0% | 45.132 | 70.145 | 6.672 | 7.634 |
| $MS_1$ | 9% | 11% | 48.143 | 72.416 | 6.845 | 7.423 |
| $MS_2$ | 11% | 9% | 53.477 | 81.014 | 7.482 | 6.884 |
| $MS_3$ | 6% | 14% | 44.189 | 65.769 | 6.126 | 7.921 |
| $MS_4$ | 8% | 12% | 46.737 | 69.366 | 6.542 | 7.721 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $MS_4$ | 10% | 10% | 49.261 | 75.221 | 6.945 | 7.141 |
| Flowability for each mix was within the range (105-115) % | | | | | | |

## VIII. CONCLUSIONS

Some conclusions are revealed from this study as follows:

1- The use of 12% of metkaoline (MK) as a partial replacement of cement increases the compressive strength of high performance mortar by about 8%. Whereas, the flexural strength has been increased by about 11% for the same level of MK replacement.

2- The use of 6% of silica fume (SF) as a partial replacement of cement increases the compressive strength of high performance mortar by about 9%. Whereas, the flexural strength has been increased by about 10% for the same level of SF replacement.

3- The combination of cementitious materials of MK and SF by the order of 11% and 9% shows compressive strength increase by about 15%. Whereas, the flexural strength has been increased by about 12% for the same level of SF and MK combination replacement.

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