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Performance of Pozzolanic Concrete Using Different Mineral Admixtures

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Abstract

Concrete is probably the most extensively used construction material in the world. However, environmental concerns regarding rapid consumption of natural resources and CO_2 emission during cement manufacturing process have brought pressure to reduce cement consumption by the use of cement replacement materials (CRMs). The utilization of calcined clay (metakaolin) and silica fume in concrete has received considerable attention in recent years. Brick powder has not got much popularity with respect to strength enhancement but it is effective to reduce drying shrinkage. The following study has been focused to determine the performance of locally available metakaolin, silica fume and brick powder as CRMs in concrete. This study focuses on compressive strength, drying shrinkage and sulfate attack properties of the concrete. Concrete cubes were used for compressive strength determination and mortar prisms for determination of drying-shrinkage and sulfate attack. 5%, 10% and 15% replacement of cement was used for all these three CRMs. Three mixtures with water-binder ratios of 0.63, 0.54 and 0.47 were prepared with a slump of 75-100mm. The sulfate attack was determined by immersing mortar prisms in 2, 5 and 10% solution of magnesium sulfate. The results revealed that silica fume concrete at optimum replacement level of 15% gave highest compressive strength. The lowest drying shrinkage was experienced in case of mortar prisms constituting brick powder. However, very low expansion was observed in SF and MK pastes and also found mutually comparable to each other.

Key Words: Silica Fume; Metakaolin; Brick powder; Compressive Strength; Durability

1. Introduction

Concrete is probably the most commonly used construction material in the world [1]. For desired characteristics of concrete, many research and modifications have been made in concrete. There is always a requirement for concrete with high durability and strength. For this requirement, blended cement concrete has been introduced. Pozzolans, also known as cementitious materials, are used in concrete constituent with normal cement as replacement materials. Originally the term pozzolan was associated with calcined earth and volcanic ashes which normally react with lime in the presence of water at ambient temperature. Nowadays, this term covers all aluminous/siliceous materials which are in fine powder form and react with calcium hydroxide in the presence of water to form compounds which have cementitious properties.

Concrete is a mixture of cement, aggregates (Coarse and fine), and water, with or without addition of admixtures. Cement is main constituent of concrete. The use of cement in concrete is increasing with time, but there have been some environmental concerns in terms of damage caused by extraction of raw materials and emission of CO_2 during cement manufacturing process. There is always pressure on construction industry to reduce the consumption of cement because each ton of cement produces approximately 1 ton of CO_2, mainly from the burning of fossil fuels and from the de-carbonation of limestone [2].The cement industry is taking measures in order to ensure a reduction in greenhouse gas emissions, using alternative fuels or changing cement composition [3].

With the development, experimentation and research in concrete technology, cement has been replaced by cement replacement materials in concrete. There are several types of cement replacement materials which are commonly used. Commonly used pozzolans are volcanic ash, volcanic tuff, pumicite, fly ash, silica-fume, metakaolin, ashes of rice husk, bagasse ash, GGBS and brick powder etc. Some of them are naturally occurring while others are by-product from industrial processes.

Silica fume also named as micro silica is by-product obtained during production of silica and ferro-silica alloys in electric arc furnace. Among all cement replacement materials, silica fume is the most effective one because of its fineness and high silica content. It is also used in concrete to improve its properties. It has been found that silica fume improve compressive strength, chloride resistance, porosity, reduction in pH, higher plastic shrinkage and other durability properties of concrete [4-7].The effect of sulfate solution on silica fume concrete has already been studied by many researchers [8-10], establishing, that, replacement of cement with SF increases the resistance against sulfate attack. Earlier studies show that the accelerated pozzolanic reaction of SF leads to accelerated shrinkage of concrete and it increases with increasing silica fume content [11-13]. It is also reported that the optimum silica fume content ranges between 15% and 25% [14,15].

Metakaolin is a reactive alumina silicate pozzolan produced by calcining kaolinite at specific temperature for specific duration. Metakaolin used in this study was developed at calcining raw kaolin at 800°C for 8 hours [16]. Studies showed that strength and durability (acid attack, porosity & shrinkage-cracking) of concrete increases with inclusion of metakaolin. Extensive research is reported in the literature concerning different properties of metakaolin paste and concrete such as pore size distribution, pozzolanic reaction, compressive strength, sulfate attack, creep and shrinkage cracking [17-20]. The effect of MK in sulfate solution has been analyzed in many studies, thus recommending its use in concrete against sulfate attack [21]. The optimum replacement level of metakaolin is between 10% and 20% [22, 23].

Brick powder, usually waste from ceramic industry may possess some pozzolanic properties. The pozzolanic reactivity of brick powder is very less and usually depends upon clay used for production of bricks or ceramics. Brick powder contribution is very less to gain strength. Brick dust used in concrete may save as much as 20 percent of cement as binding material, while providing the same strength or increase in strength in some cases. The durability properties of concrete containing brick powder were found to be comparable to normal concrete [24].

2. Experimental Programme

2.1 Materials Used

The materials used for experimental program were cement, sand, aggregate, silica fumes, metakaolin, brick powder, super plasticizer and water.

Cement was ordinary Portland cement manufactured according to Pakistan standard PSS 232-1883 (R) and British Standard EN 197.The sand used in this study was properly graded according to ASTM standard. Its specific gravity and fineness modulus was 2.5 and 2.48 respectively. Silica Fume was obtained from the market with the reported properties shown in Table-1. Metakaolin was prepared from kaolin clay and then grounded to the given Blaine's value as specified in Table-1. Brick Powder was obtained by crushing and sieving under-burnt bricks from kilns. Aggregate used in this study is Margalla crush having a maximum size passing through 19 mm sieve size with specific gravity 2.63. Chemrite D-620, second generation water reducing admixture, was used as super plasticizes to maintain the workability of concrete. The physical and chemical properties are given in table-1. The chemical composition of the brick powder reflect only those compounds linked in the hydration of the cement.

2.2 Specimens preparation

Three series of concrete mixtures were developed for strength performance as shown in table-2 and other three series with same matrix ratios as used in concrete mixtures were used for shrinkage and sulfate attack for mortar preparation as displayed in table-3. Water-binder ratios of 0.63, 0.54 and 0.47 were used for the preparation of mixture belonging to series I, II and III for targeted strength of 20Mpa, 27Mpa and 35Mpa.

Table 1 Physical and chemical composition of cement and CRMs

	Cement	SF	MK	BP
Physical Properties				
Specific Gravity	3.15	2.22	2.5	2.64
Surface Area (m^2/Kg)	330	1550	645	510
Chemical Properties (%)				
CaO	61.94	0.2	0.015	4.65
SiO_2	18.08	92	57.1	23.12
Al_2O_3	5.58	0.7	36.24	15.09
Fe_2O_3	2.43	1.2	0.91	6.65
MgO	2.43	0.2	0.19	1.94
SO_3	2.54	0.3-0.7	-	0.36
K_2O	0.99	1	3.11	2.34
Na_2O	0.18	1	0.009	0.78
LOI	4.4	3.5	2.5	2.33

In this study, control and other mixtures were prepared for each series with a control slump of 75-100 mm. These control mixtures were modified by replacing cement with 5%, 10% and 15% of CRMs as shown in Table-2.

Twelve concrete cylinders were cast for each mix proportion. Concrete was poured in two layers into the cylindrical moulds and compacted by vibrating table after each pour. The slump of each mix was kept in the range of 75 mm to 100 mm. The cylinders were removed from their moulds after 24 hours and cured in curing tank at room temperature.

Table 2: Mix Proportions for concrete

Series	**Designation**	**Binder (Kg/m³)**			**Aggregate (Kg/m³)**		**Water (Kg/m³)**	**Compressive Strength (Mpa)**	
		Cement	**CRMs**		**Fine**	**Coarse**		**Days**	
			Type	**Weight**				**28**	**90**
1	**C362**	362	-	-	671	1323	228	19.5	21.1
	C362MK05	344	MK	18				21.1	22.9
	C362MK10	326		36				20.0	22.2
	C362MK15	308		54				19.1	21.5
	C362SF05	344	SF	18				27.2	28.9
	C362SF10	326		36				30.0	35.0
	C362SF15	308		54				33.9	36.8
	C362BP05	344	BP	18				21.1	22.0
	C362BP10	326		36				17.8	20.2
	C362BP15	308		54				17.1	18.0
2	**C393**	393	-	-	589	1374	212	27.0	28.5
	C393MK05	375	MK	18				29.1	30.8
	C393MK10	357		36				30.5	34.0
	C393MK15	339		54				31.0	33.1
	C393SF05	344	SF	18				31.1	33.2
	C393SF10	326		36				34.9	39.4
	C393SF15	308		54				40.0	45.8
	C393BP05	344	BP	18				28.0	31.2
	C393BP10	326		36				23.2	27.6
	C393BP15	308		54				21.0	24.0
3	**C428**	428	-	-	578	1349	201	33.1	36.0
	C428MK05	428	MK	18				35.0	39.1
	C428MK10	428		36				42.2	44.8
	C428MK15	428		54				43.0	48.1
	C428SF05	428	SF	18				39.0	42.2
	C428SF10	428		36				45.1	48
	C428SF15	428		54				47.3	54.0
	C428BP05	428	BP	18				35.0	37.1
	C428BP10	428		36				30.9	35.0
	C428BP15	428		54				26.2	29.9

- CXXX MK/SF/BP YYY
  Where CXXX represent cement content in Kg/m^3, MK Metakaolin, SF silica fume, BP Brick powder, YYY Replacement level.

Table 3: Mix Proportions for mortar

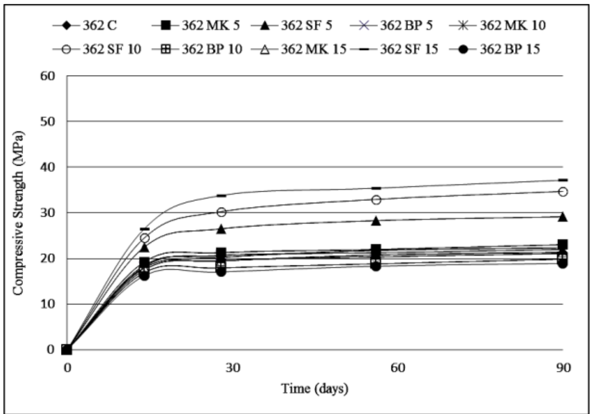
Series	Designation	Binder (Kg/m^3)			Fine Aggregate (Kg/m^3)	Water (Kg/m^3)
		Cement	CRMs			
			Type	Weight		
1	**C758**	758	-	-	1403	477
	C758MK05	720	MK	38		
	C758MK10	682		76		
	C758MK15	644		114		
	C758SF05	720	SF	38		
	C758SF10	682		76		
	C758SF15	644		114		
	C758BP05	720	BP	38		
	C758BP10	682		76		
	C758BP15	644		114		
2	**C865**	865	-	-	1297	467
	C865MK05	822	MK	43		
	C865MK10	779		86		
	C865MK15	736		129		
	C865SF05	822	SF	43		
	C865SF10	779		86		
	C865SF15	736		129		
	C865BP05	822	BP	43		
	C865BP10	779		86		
	C865BP15	736		129		
3	**C920**	920	-	-	1242	432
	C920MK05	874	MK	46		
	C920MK10	828		92		
	C920MK15	782		136		
	C920SF05	874	SF	46		
	C920SF10	828		92		
	C920SF15	782		136		
	C920BP05	874	BP	46		
	C920BP10	828		92		
	C920BP15	782		136		

- CXXX MK/SF/BP YYY
  Where CXXX represent cement content in Kg/m^3, MK Metakaolin, SF silica fume, BP Brick powder, YYY Replacement level

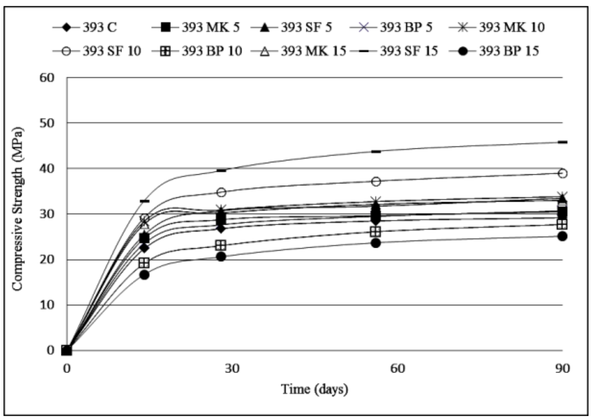
Four mortar prisms were cast for drying shrinkage and six mortar prisms were cast for determination of expansion due to sulfate attack. Mortar was poured in two layers and compaction was done by compacting rod. The moulds were removed after 24 hours of casting and then cured in lime saturated water for 48 hours

2.3 Test Method

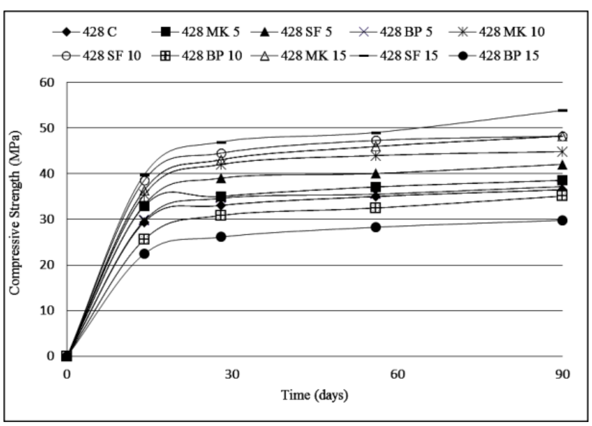
Concrete cylinders of size 100 mm x 200 mm (diameter x height) dimensions were used for compressive strength and mortar prisms of size 25 mm x 25 mm x 285 mm were used for drying shrinkage and sulfate attack tests. The results obtained were the average of all samples at each age. Compressive strength test was conducted according to guidelines of ASTM C 39-04a after 28 and 90 days of moist curing while drying shrinkage and sulfate attack test were performed according to guidelines of ASTM C596-01 and ASTM C 1012-03 respectively. The observations were recorded at age of 3, 4, 11, 18, 25, 32, 56 and 90 days for drying shrinkage test while sulfate attack test observation recorded at age of 7, 14, 21, 28, 56, and 90 days after curing. Expansion test was conducted by immersing prisms in a solution of magnesium sulfate ($MgSO_4$) with varying concentration of 2%, 5% and 10%. The PH-value of each solution was kept in the range of 6 to 9.



a) At binder content of 362 Kg/m^3



b) At binder content of 393 Kg/m^3



c) At binder content of 428 Kg/m^3

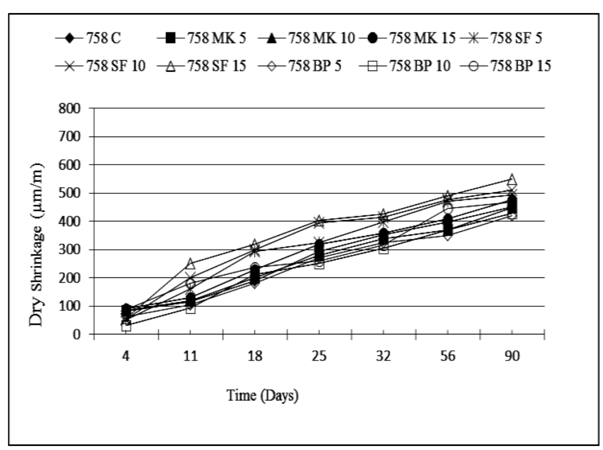
Fig.1 Compressive Strength of Pozzolanic Concrete at 5%, 10% and 15% Cement Replacement.

2.4 Test results and discussion

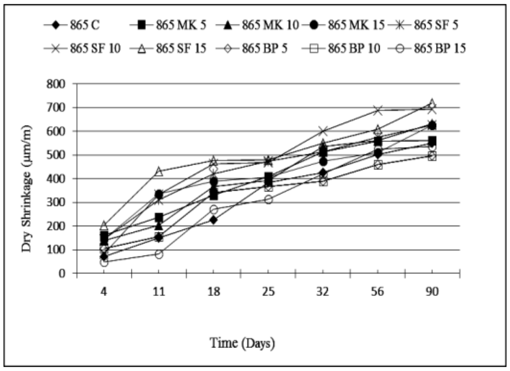
Figure 1 (a, b& c) show graphical comparison of compressive strength of control and pozzolanic concrete at 28 and 90 days for different binder contents of 362Kg/m^3, 393Kg/m^3 and 428 Kg/m^3 with respective water-binder ratios of 0.63, 0.54 and 0.47 respectively.

Results of compressive strength show that at each age of testing, the concrete with 15% cement replacement by silica fumes gained the highest compressive strength than respective control concrete as well as those concretes with other pozzolanic materials i.e. metakaolin and brick Powder. The compressive strength of silica fume increases with increase in replacement level of cement content. Metakaolin shows increase in compressive strength at higher cement content but not much effective at lower cement content. The pozzolanic behavior of brick powder is very less at each cement content however slight increase in compressive strength observed at 5% cement replacement. Percentage increase in compressive strength, for silica fume, decreases with increase in cement content while metakaolin shows opposite behavior. The maximum increase in compressive strength is 75% for silica fume at 362 Kg/m^3, 29% for metakaolin at 428 Kg/m^3 and only 5% for brick powder at 428 Kg/m^3. The increase in strength for SF and MK concrete is attributed to the fact, that both of them due to their fineness and pozzolanic action reduces calcium hydroxide and total voids within concrete thus resulting in more stronger concrete.

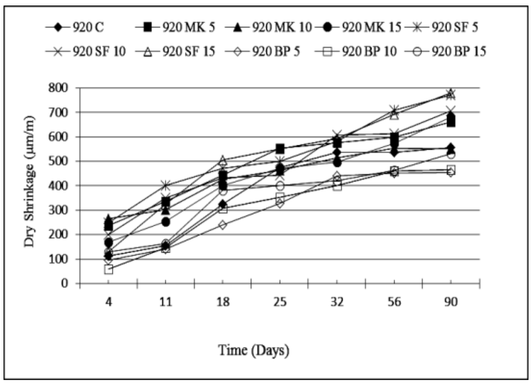
The comparisons of drying shrinkage of control and different CRMs mortars are graphically represented in Figures 2-(a, b& c) at age of 4, 11, 18, 25, 32, 56 and 90 days for binder content of 758 Kg/m^3, 865 Kg/m^3 and 920 Kg/m^3 with respective water-binder ratio of 0.63, 0.54 and 0.47 respectively.



a) At binder content of 758 Kg/m^3



b) At binder content of 865 Kg/m^3



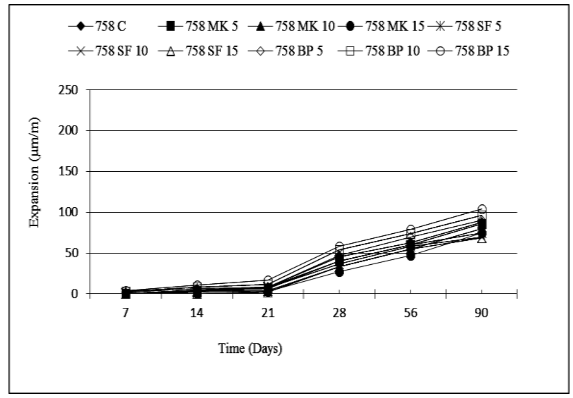
c) At binder content of 920 Kg/m^3

Fig. 2 Drying Shrinkage Comparison of Different CRMs at different Binder Content.

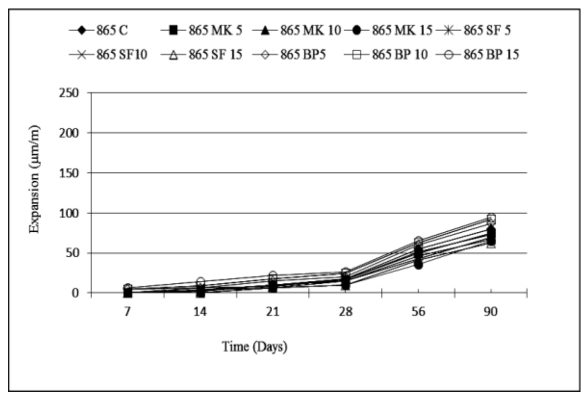
It is observed that silica fume attains highest drying shrinkage at each testing age and all cement contents. Here it can be observed that metakaolin drying shrinkage is higher than respective control concrete but less than that of silica fume mortar. Drying shrinkage of brick powder is very less than control mortar and gives very positive results at all cement content.

Drying shrinkage of silica fume and metakaolin increases with increase in replacement level as well as increase in cement content. The behavior of brick powder is opposite to that of metakaolin and silica fume i.e. its drying shrinkage decreases with increase in replacement level. The magnitude of drying shrinkage increases with increase in cement content for all pozzolanic materials. Shrinkage is linked with the cement content, higher the cement content higher will be the shrinkage. Since, metakaolin and silica fume are also cementing materials, therefore, they play a vital role in the increase of shrinkage. The brick powder is acting like a filler material; therefore, reducing the cement content of a given mix, hence reducing shrinkage.

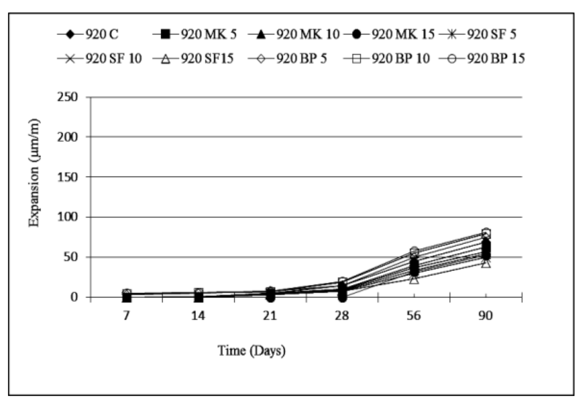
The comparisons for expansion due to external sulfate attack of 2%, 5% and 10% $MgSO_4$ solution of control and CRMs mortars are graphically represented in Figures 3-(a, b &c), 4-(a, b & c) and 5-(a, b & c) respectively at age of 7, 14, 21, 28, 56 and 90 days for binder content of 758 Kg/m^3, 865 Kg/m^3 and 920 Kg/m^3 with respective water-binder ratios of 0.63, 0.54 and 0.47.



a) At binder content of 758 Kg/m^3

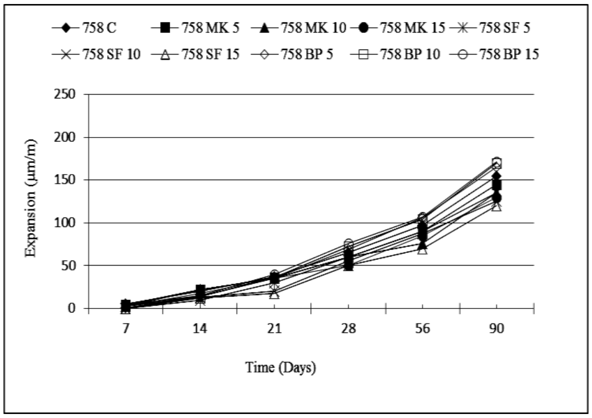


b) At binder content of 865 Kg/m^3

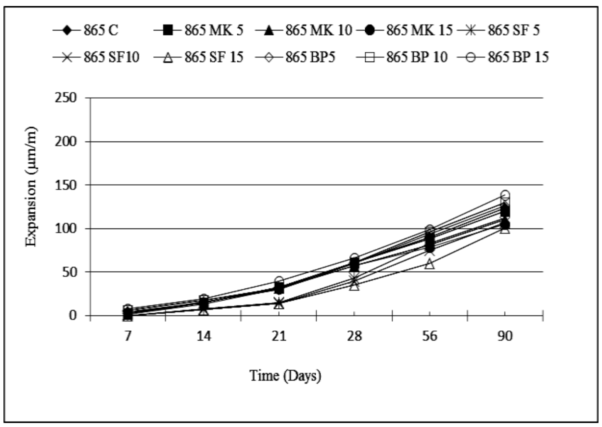


c) At binder content of 920 Kg/m^3

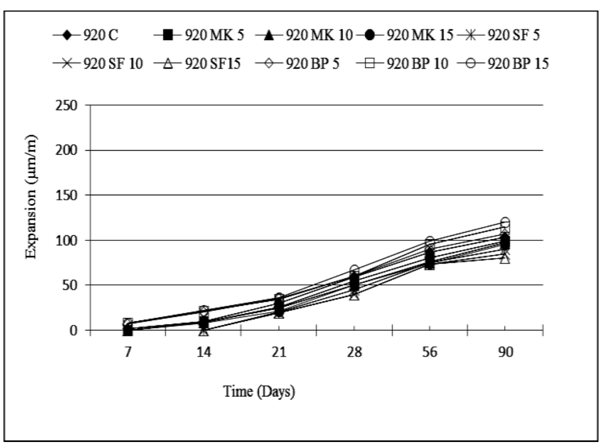
Fig.3 Expansion Comparison of Different CRMs at different Binder Content in 2%$MgSO_4$ Solution



a) At binder content of 758 Kg/m^3

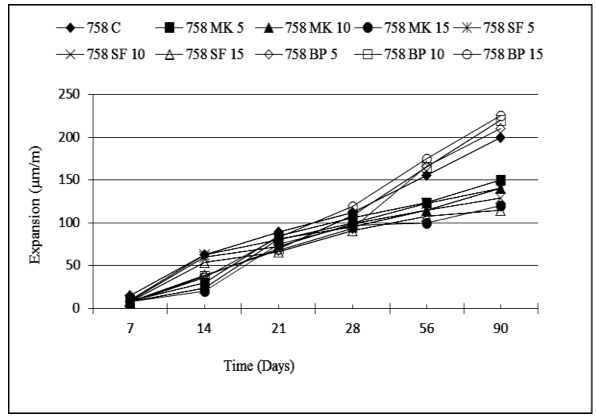


b) At binder content of 865 Kg/m^3

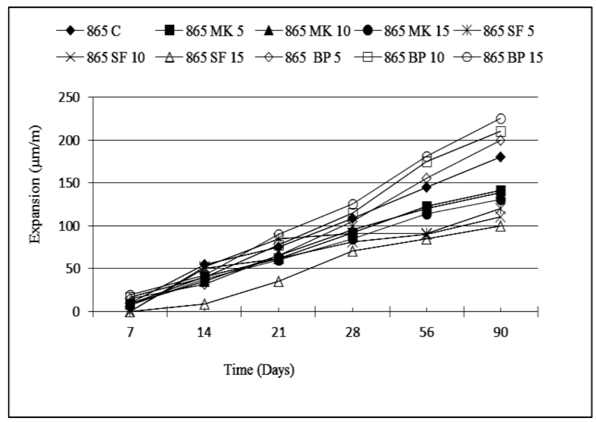


c) At binder content of 920 Kg/m^3

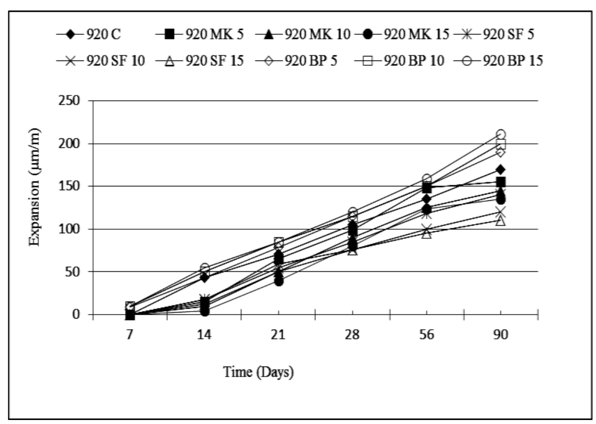
Fig. 4 Expansion Comparison of Different CRMs at different Binder Content in 5% $MgSO_4$ Solution.



a) At binder content of 758 Kg/m^3



b) At binder content of 865 Kg/m^3



c) At binder content of 920 Kg/m^3

Fig. 5 Expansion Comparison of Different CRMs at different Binder Content in 10% $MgSO_4$ Solution.

The expansion values of metakaolin and silica fume is less than respective control concrete but are very close to each other. The difference between expansion of brick powder and control mortar is very high at 15% replacement level. Expansion in mortar prisms containing brick powder increases with increase of replacement level of brick powder while decreases in case mortar prisms containing silica fume and metakaolin.

The magnitude of expansion is directly proportional to $MgSO_4$ solution concentration but inversely proportional to cement content i.e. it increases as concentration of $MgSO_4$ solution increases but decreases with increase in cement content. The results of expansion due to external sulfate attack as presented in figure 3-5 clearly indicate that brick powder gives highest expansion due to external sulfate attack at each testing age and at all cement contents.

Expansion is caused by the chemical action between sulfates and calcium hydroxide. Since silica fume and metakaolin eats up calcium hydroxide when used as supplementary cementing material, therefore, causing less expansion in comparison to brick powder.

3. Conclusions

Based on the results of experimental work, the following conclusions are drawn:

1) Metakaolin improves the compressive strength at higher cement content, enhances sulfate attack resistance but increases shrinkage.
2) Silica fume improves compressive strength at all cement contents. It also improves resistance to sulfate attack but shows highest shrinkage among all mineral admixtures used in this study.
3) Brick powder only improves shrinkage but is more susceptible to sulfate attack and higher replacement leads to decrease in compressive strength.
4) The increase in concentration of sulfate solution increases the expansion in cement mortars.
5) Increase in percentage replacement level of metakaolin and silica fume reduces expansion in mortar but opposite trend is observed in brick powder.

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