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Compressive strength and sulfate resistance of limestone and/or silica fume mortars

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ABSTRACT

In this study, compressive strength and sulfate resistance of mortars containing silica fume and/or limestone in different replacement levels were examined. For this purpose, limestone was used as 5%, 20%, 35% and silica fume was used as 5%, 10%, 15% by weight of cement. Sixteen different blended cements were prepared containing limestone and/or silica fume in different ratios. Mortar mixtures were prepared using these 16 cements. Flow values and 2, 7, 28, 90, 180 day-compressive strengths of the mortar mixtures were determined. In addition, sulfate resistances of mortars were separately determined in sodium and magnesium sulfate solutions. Consequently, it was seen that negative effect of silica fume on workability of mortars and limestone on compressive strength of mortars can be compensated by using limestone and silica fume together. Simultaneous use of limestone and silica fume was showed to increase sulfate resistance of mortars.

1. Introduction

Silica fume is a by product from electric furnaces used in the manufacture of silicon metal or silicon alloys [1–5]. It is well known that, this product has several advantages such as high ultimate strength, high sulfate resistance and low heat of hydration when used in Portland cement concrete. These advantages derived from high specific surface and pozzolanic activity of silica fume particles [1–3,6–8]. Limestone is used for various aims in cement and concrete, as a raw material of clinker, as aggregate in concrete and an additive in cement [6]. The usage of limestone powder in cement has several advantages such as, high early strength, high workability, low water requirement, low production cost of concrete and low CO_2 emission in the cement production [9–13]. Portland limestone cements can be produced by partial replacement of limestone from 6% to 35% according to European Standard EN 197-1 [14].

The aim of this study was to investigate simultaneous effect of silica fume and limestone on compressive strength and sulfate resistance of mortars. In this scope, mortars containing various amounts of silica fume (5%, 10%, 15% by weight of cement) and/or limestone (5%, 20%, 35% by weight of cement) were prepared. Then flow values and 2, 7, 28, 90, 180 days uniaxial compressive strengths as well as sodium and magnesium sulfate resistances of these mortars were determined. As a result, it was seen that simultaneous using of limestone and silica fume improved properties of mortars which investigate in this study.

2. Experimental study

CEM I 42.5 type normal Portland cement, limestone and silica fume were used in the experimental study. Chemical compositions of these materials are presented in Table 1. The Blaine surface of limestone is 420 m^2/kg and specific surface of silica fume is 18,000 m^2/kg. Sixteen different cement mixtures were prepared using the above mentioned materials in various proportions as summarized in Table 2.

Flow values, compressive strengths (2, 7, 28, 90, 180 days) and sulfate resistance of mortars prepared from these 16 cements were determined. 50 × 50 × 50 mm cube mortar specimens were prepared by using 450 g cement, 1350 g standard sand and 0.5 water/binder ratio for determination of compressive strength of mortars. The strength values given in this study are the average of six specimens. Flow values of mortar mixtures were determined according to ASTM C1437. The average of four measurements was used for determination of flow values.

Sulfate resistances of mortars were determined according to ASTM C1012 test procedure. 25 × 25 × 285 mm prismatic specimens and 50 × 50 × 50 mm cube specimens were prepared from each mortar mixtures. All specimens were cured in standard curing conditions until cube specimens gained compressive strength of 20 MPa. After reaching compressive strength of 20 MPa, prismatic specimens were separately kept in 5% sodium sulfate and 4.2% magnesium sulfate solutions. The change in length of the specimens was measured periodically. Three specimens were tested for each mortar mixture.

3. Results and discussion

3.1. Flow table test results

As it can be seen from Table 3, flow values of mortars decreased with increasing silica fume content. Silica fume, up to 5% replacement level, does not have a significant effect on the workability of mortar. Beyond this replacement level (i.e. in the mixtures containing 10% and 15% silica fume) flow values lower than that of control mixture containing no silica fume recorded. It seems that, in 5% silica fume replacement level, the circular and ultra fine silica fume

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Table 1
Chemical composition of materials used in study.

%	Cement	Limestone	Silica fume
SiO_2	19.65	0.52	90.26
Al_2O_3	4.47	0.34	0.63
Fe_2O_3	3.56	0.29	0.33
CaO	62.53	54.32	3.18
MgO	2.40	0.42	0.33
SO_3	2.64	0.04	–
C_3S	55.45	–	–
C_2S	14.51	–	–
C_3A	5.82	–	–
C_4AF	10.83	–	–

Table 2
Mixture proportions.

Mixture	Cement (%)	Limestone (%)	Silica fume (%)
Control	100	0	0
5L	95	5	0
20L	80	20	0
35L	65	35	0
5S	95	0	5
10S	90	0	10
15S	85	0	15
5L5S	90	5	5
5L10S	85	5	10
5L15S	80	5	15
20L5S	75	20	5
20L10S	70	20	10
20L15S	65	20	15
35L5S	60	35	5
35L10S	55	35	10
35L15S	50	35	15

Table 3
Flow values of mortars.

Mixture	Flow value (mm)	Relative flow values (%)
Control	131	100
5L	139	106
20L	140	107
35L	147	112
5S	130	99
10S	128	98
15S	122	93
5L5S	133	102
5L10S	127	97
5L15S	125	95
20L5S	136	104
20L10S	132	101
20L15S	129	98
35L5S	139	106
35L10S	135	103
35L15S	132	101

particles enter the relatively coarse cement interparticle space, push the interparticle water outwards. Thus, the water acts as free water contributing to the workability of the mixture. On the other hand, owing to the high surface area of silica fume particles at high replacement levels, silica fume increases the water requirement of the mixture, or reduces the workability for given water content which is the case in this study [15,16].

On the contrary, flow values of mortars increased with increasing limestone content of cement. Compared to control mixture, even 5% limestone replacement affected the flow value positively. The effect is more pronounced in 35% limestone-incorporated cement. Since grindability of limestone is higher than that of clinker, ground limestone has a wider grain size distribution than cement. Thus, fine granulated limestone particles fill wide pores among cement particles and reduce water requirement [13,17,18].

Flow values of limestone–silica fume mortars were generally lower than flow values of mixtures containing only limestone and higher than flow values of mixtures containing only silica fume. Therefore, negative effect of silica fume on workability was compensated by simultaneous using of silica fume with limestone in cement. The effect of limestone on flow values of limestone–silica fume mortars increased with increasing limestone content. Considering with flow values of mortars, the optimum limestone–silica fume mortar is 35L5S containing 35% limestone and 5% silica fume.

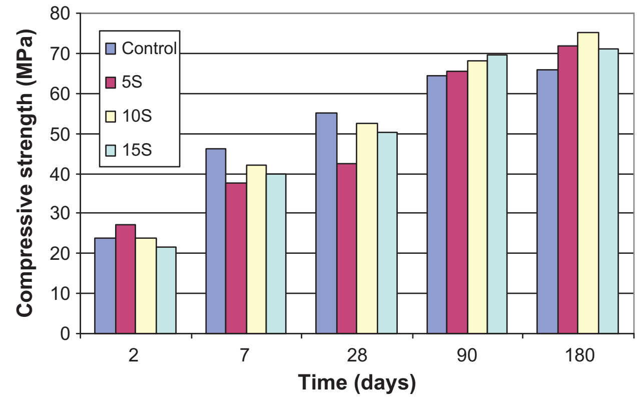

Fig. 1. Compressive strength values of cements containing only silica fume.

3.2. Compressive strength test results

Compressive strength of mortars containing only silica fume are shown in Fig. 1. In addition, the effect of silica fume addition on relative compressive strengths is given in Table 4. Compressive strength values of silica fume mortars are generally lower than control mixtures up to 28 days. Beyond this age, compressive strengths of silica fume-incorporated mixtures are higher than that of control mixtures. As it is well known, being a highly pozzolanic material, silica fume forms additional calcium silicate hydrate by reaction with calcium hydroxide formed upon cement hydration. This results in increase in the strength of the blended cement. Since at early ages of hydration of cement sufficient amount of calcium hydroxide is not available, the early strength of blended cements is lower than that of ordinary cements.

Considering the compressive strength of mortars, it is obvious that optimum silica fume content is 10%. Compressive strength of silica fume mortars generally decreased at 15% silica fume inclusion level because of increasing water requirement and decreasing workability by high silica fume replacement. As it was mentioned earlier, 15% silica fume replacement reduced similarly the flow values of mortars.

Compressive strengths of mortars containing only limestone are shown in Fig. 2. In addition, the effect of limestone addition on relative compressive strengths is given in Table 4. Compared to control mortar mixture, limestone inclusion reduced compressive strength values and these reductions increased with increasing limestone content. The reason lies in the reduction of hydraulically active clinker fraction of cement upon the limestone replacement [17]. Cement dilution effect of limestone becomes more effective at 35% limestone replacement level especially at later ages.

Table 4
Relative compressive strength values.

Mixture	Relative compressive strength values (%)				
	2 days	7 days	28 days	90 days	180 days
Control	100	100	100	100	100
5L	94	84	95	87	97
20L	73	74	76	76	85
35L	50	60	59	53	62
5S	113	82	77	102	109
10S	100	91	95	105	114
15S	90	87	91	108	108
5L5S	77	74	82	104	109
5L10S	71	62	81	100	103
5L15S	67	63	86	99	105
20L5S	63	46	68	84	89
20L10S	69	47	75	83	89
20L15S	65	51	67	81	83
35L5S	42	42	56	60	69
35L10S	33	35	55	64	67
35L15S	38	27	62	64	64

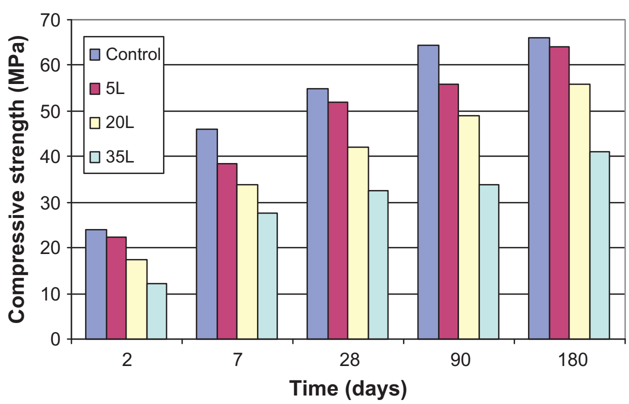

Fig. 2. Compressive strength values of mortars containing only limestone.

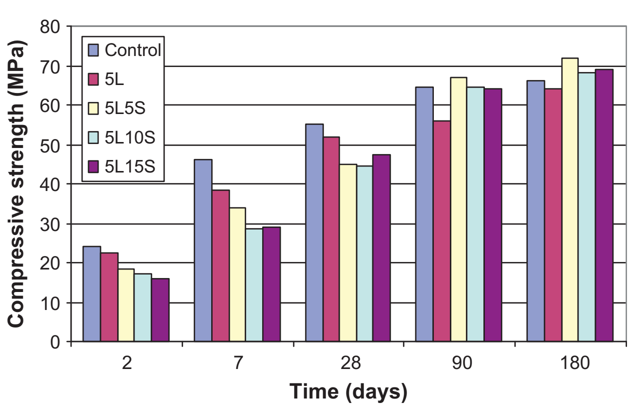

Fig. 3. Compressive strength values of limestone–silica fume mortars containing 5% limestone.

Compressive strengths of limestone–silica fume mortars are shown in Figs. 3–5. In addition, the effects of limestone and silica fume addition on relative compressive strengths are given in Table 4. Compressive strengths of limestone–silica fume mortars were lower than that of those containing only limestone up to 28 days. However, at later ages, due to pozzolanic effect of silica fume, opposite results were recorded. Limestone–silica fume mortars containing 20% and 35% limestone showed lower compressive strength values than control mortar. Mortars containing 5% limestone showed similar compressive strength values at 90 and 180 days compared to control mortar. It can be derived from the low limestone inclusion level and consequently low dilution effect of limestone. Differences between compressive strength values of limestone-silica fume mortars and control mortar were generally higher at early ages compared to those at later ages. Considering the compressive strength values of mortars, the optimum limestone–silica fume mortar is 5L5S containing 5% limestone and 5% silica fume.

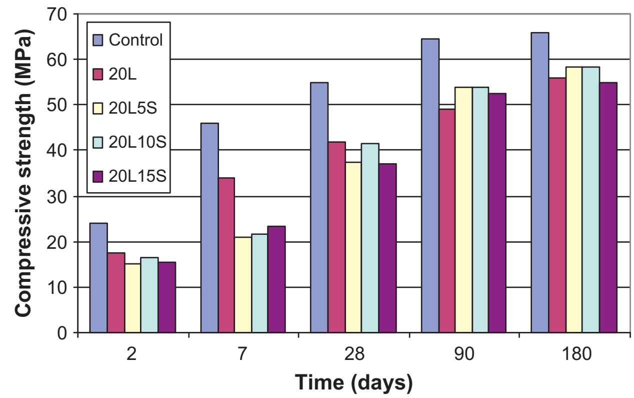

Fig. 4. Compressive strength values of limestone–silica fume mortars containing 20% limestone.

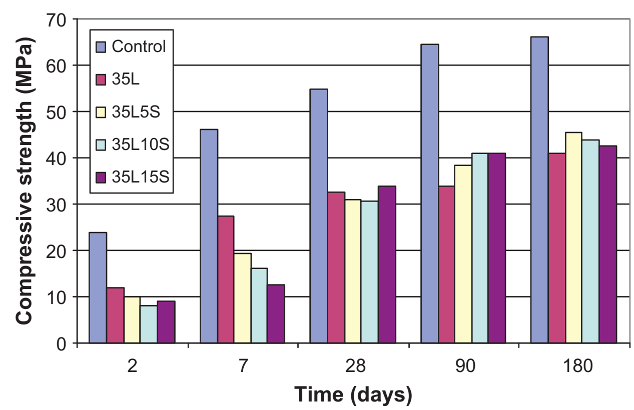

Fig. 5. Compressive strength values of limestone–silica fume mortars containing 35% limestone.

3.3. Sulfate expansion test results

Expansion values of mortars containing only limestone and silica fume in sodium and magnesium sulfate solutions are shown in Figs. 6 and 7, respectively. Expansions of these mortars were lower than control mortars. However, this reduction was lower in limestone-incorporated mortars than silica fume-containing mortars. Little reduction of expansion values of limestone mortars are attributed to the reduction of the amount of cement portion of limestone cements used in these mortars. As a result, C_3A content of cement decreased and ettringite formation which is occurred as a result of sulfate attack reduced. Similarly, C_3S and C_2S contents of cement decreased and gypsum formation upon sulfate attack on calcium hydroxide reduced. In the same way, due to pozzolanic reaction, silica fume reduced the available calcium hydroxide, thus, reduced the gypsum formation upon sulfate attack on silica fume-incorporated mixtures.

Expansion values of limestone–silica fume mortars are shown in Figs. 8–10. Simultaneous using of limestone and silica fume decreased expansion values. This reduction was increased with

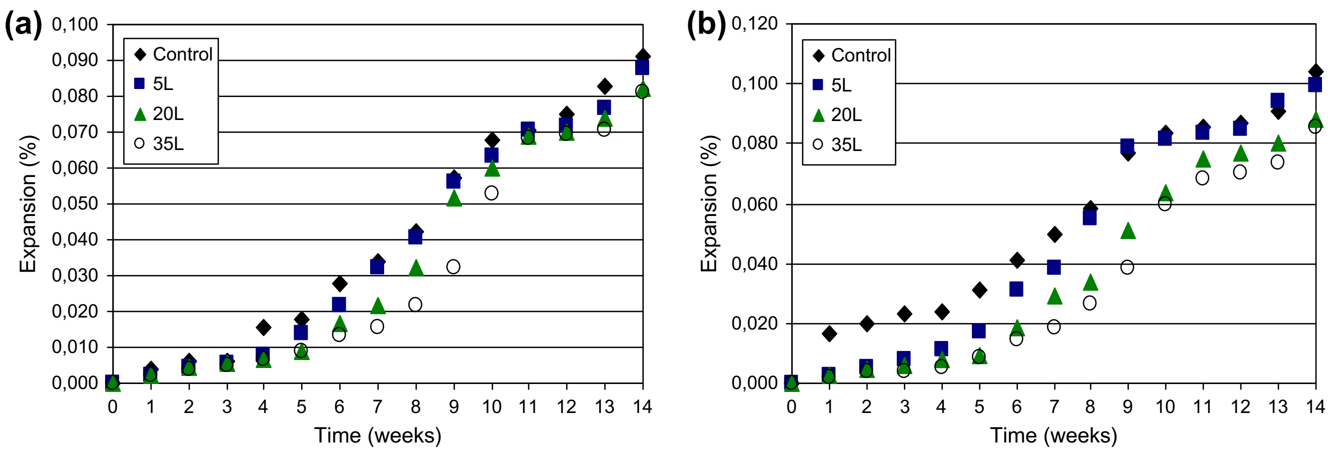

Fig. 6. Expansion of mortars containing only limestone in (a) Na_2SO_4 and (b) $MgSO_4$ solution.

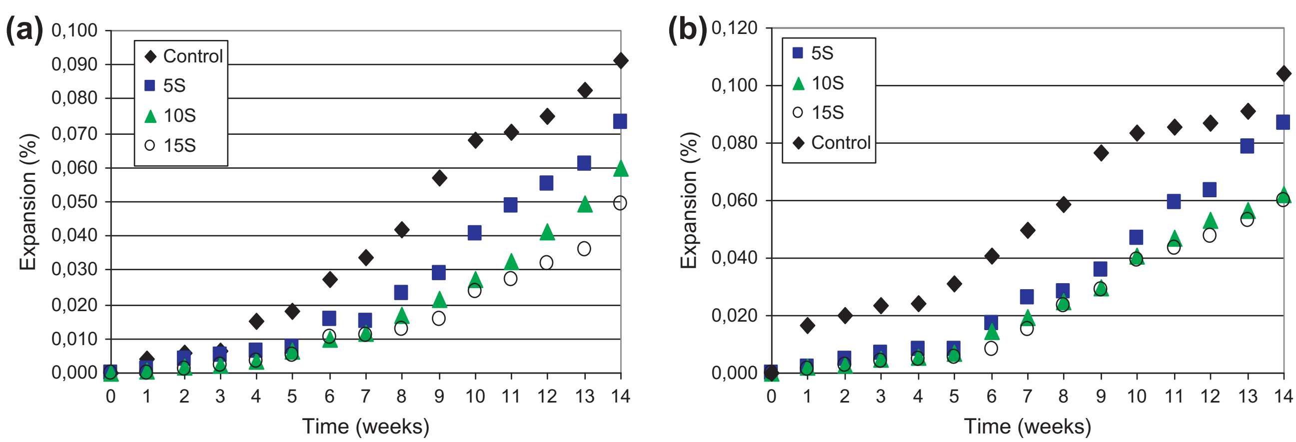

Fig. 7. Expansion of mortars containing only silica fume in (a) Na_2SO_4 and (b) $MgSO_4$ solution.

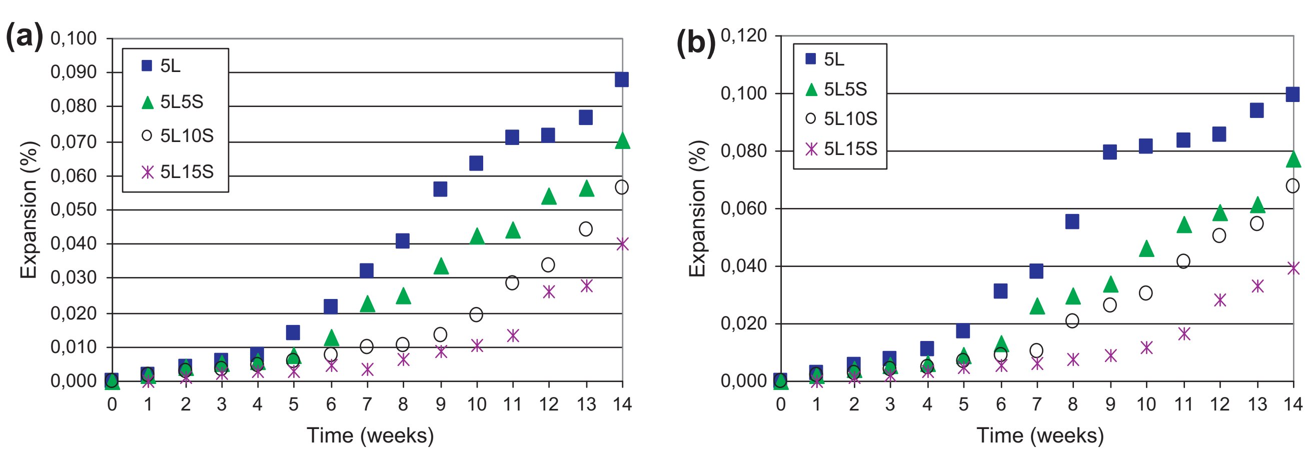

Fig. 8. Expansion values of mortars containing 5% limestone in (a) Na_2SO_4 and (b) $MgSO_4$ solution.

increasing limestone content. Using of silica fume in mortars containing 35% limestone significantly decreased expansion values. The differences between the sulfate expansion values of limestone–silica fume mortars containing different amounts of silica fume reduce by the increase in limestone content of the cement. Considering the sulfate expansion values of mortars, the optimum limestone–silica fume mortar is 35L15S containing 35% limestone and 15% silica fume.

The beneficial effect of silica fume in reducing sulfate expansion of the mortar becomes more obvious in the mixture with higher limestone contents. As it was mentioned earlier, since the water/cementitious material ratio of the mixtures is kept constant in this study, the workability of silica fume-incorporated mixtures is considerably lower than control or limestone incorporated mixtures. The lower compatibility seems to increase the permeability of the mix and provides greater ingress of sulfate solution into the

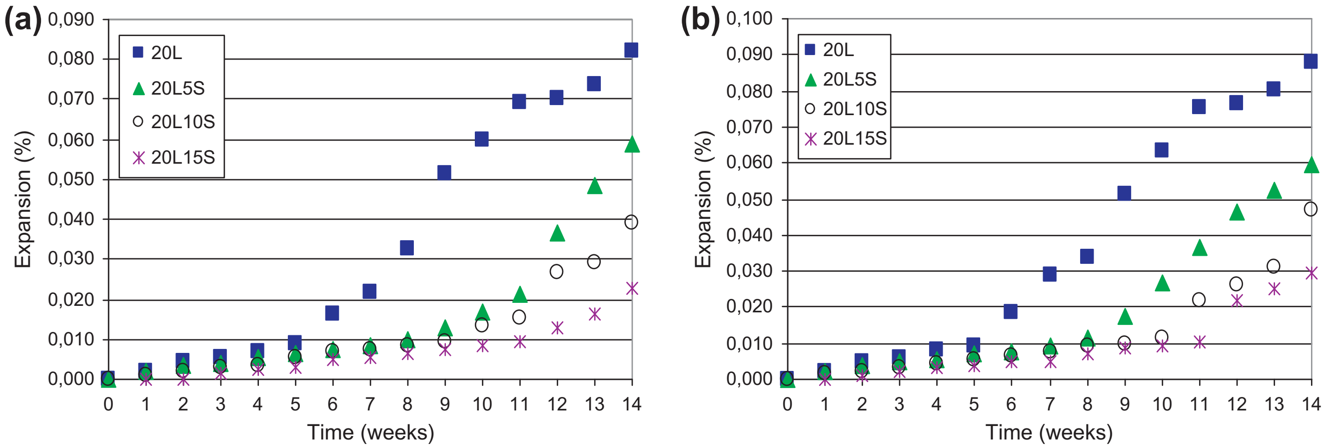

Fig. 9. Expansion values of mortars containing 20% limestone in (a) Na_2SO_4 and (b) $MgSO_4$ solution.

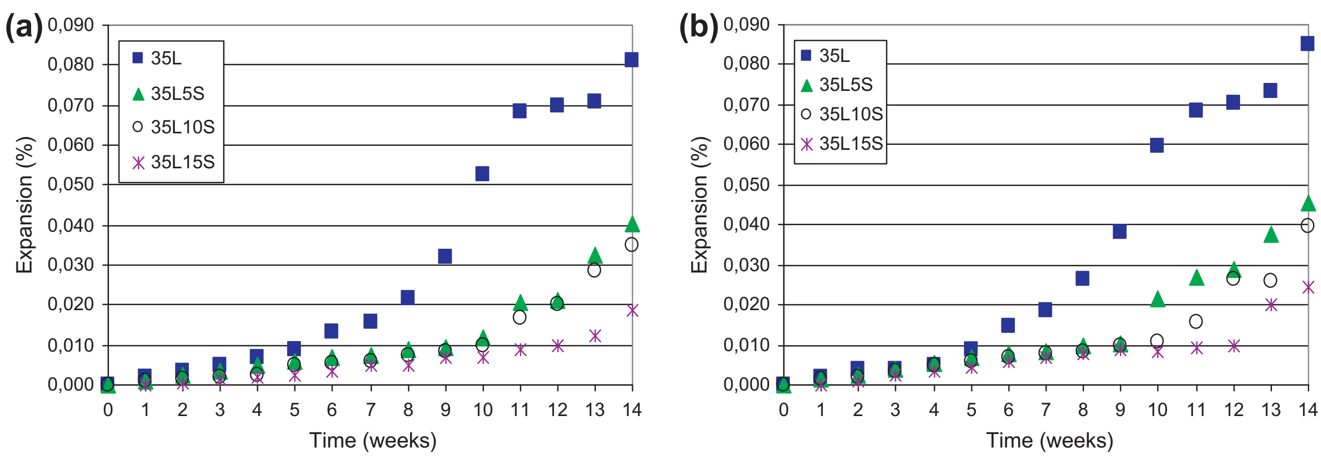

Fig. 10. Expansion values of mortars containing 35% limestone in (a) Na_2SO_4 and (b) $MgSO_4$ solution.

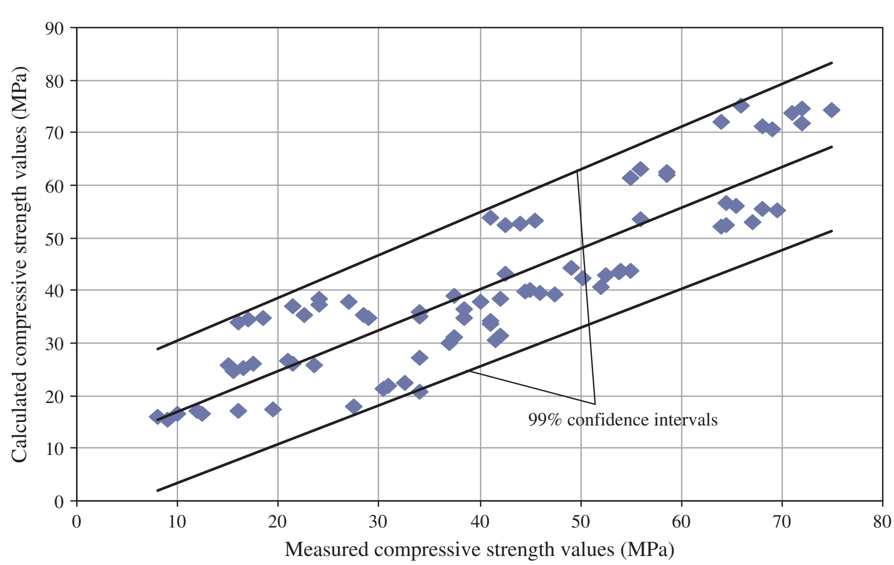

Fig. 11. Measured and predicted compressive strength values.

specimen. It seems that simultaneous use of silica fume and limestone in cement compensates to some extent, the negative effect of silica fume on workability. Contribution of limestone to the workability of mortar and resultantly reducing the permeability of the mixture is probably another reason for lower sulfate expansion of limestone incorporated cements.

Furthermore, expansions of all mortar mixtures in magnesium sulfate solution were higher than that of sodium sulfate solutions.

This is due to the fact that, magnesium ion can completely replace the calcium in hydrated Portland cement, thus, magnesium sulfate is potentially more destructive compared to sodium sulfate. Magnesium sulfate is highly soluble and resultantly composes sulfate solutions with high concentration than sodium sulfate [19]. This is probably another reason for higher magnesium sulfate expansion of mortars.

3.4. Statistical evaluation of test results

A multiple linear regression analysis was used to obtain the following relationships:

$$CS = -0.6122 \times L - 0.0973 \times S + 0.2068 \times T + 37.9776 \quad (1)$$

where CS is the compressive strength of mortar (MPa); L is the limestone content (%); S is the silica fume content (%); T is the time (days). The relationship between measured and predicted compressive strength values (obtained from Eq.(1)) as well as 99% confidence intervals are shown in Fig. 11. The coefficient of correlation between measured and predicted values is 88%. As can be seen from the correlation value, the predicted values are in a good agreement with the measured values obtained in this study.

4. Conclusion

The following conclusions can be drawn from the experimental study:

- The negative effect of silica fume on workability of mortars can be compensated by using of limestone and silica fume together.
- In limestone–silica fume mortars, to some extent, silica fume compensated the negative effect of limestone on compressive strength of mortars at later ages.
- Simultaneous using of limestone and silica fume was significantly increased sulfate resistance of mortars.
- Sulfate expansions of all mortar mixtures in magnesium sulfate solution were higher than in sodium sulfate solutions.
- The optimum limestone–silica fume mortars for fluidity, compressive strength and sulfate resistance were obtained as 35L5S, 5L5S and 35L15S, respectively.

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