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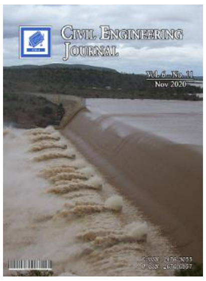

Effect of Admixtures on Mechanical Properties of Cementitious Mortar

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Abstract

In the current study, the primary focus is to investigate the effect of Styrene Butadiene Rubber (SBR), silica fume and fly ash on compressive and flexure strengths of cementitious mortar. Three types of specimens are prepared; the first series comprises of control specimen; the second one consists of the mortar's specimen modified with SBR and the third one consists of the mortar's specimen modified with SBR in a combination of fly ash and silica fumes. Mortar samples are cast in the weight ratio of 1:2.75 (cement: sand). The SBR is added at a rate of 20% of the mass of cement. The water to cement ratio (W/C) is kept at 0.5 for control specimens and the quantity of mixing water in SBR-containing samples is reduced by the same amount as the SBR is added: The adjustment is meant to obtain same consistency for all the specimens. 20% fly ash and 2.5% silica fume are added to the mortar as replacement of cement. Compressive and flexure tests are carried out according to ASTM standards. Moreover, SEM is also performed on samples at the age of 28 days. Studies reveal that SBR and SCMs reduce the mechanical strength of the mortars. SEM and EDS studies show that SBR hinders the formation of albite, whereas silica content from silica fumes and fly ash converts CaCO3 to Wollastonite (a white loose powder), which is responsible for the reduction of mechanical strength. The study also confirms that the addition of SBR in place of water hinders the formation of primary and secondary hydration products.

Keywords: Cementitious Composites; Mortar; Styrene Butadiene Rubber; Silica Fumes; Fly Ash; Mechanical Properties; SEM.

1. Introduction

A material that imparts plasticity, consistency, and bonding properties when mixed with water with or without aggregate is designated as cementitious material [1]. Supplementary cementitious materials are used as a partial or complete substitution of ordinary Portland cement in concrete mixtures. The resultant mix improves the workability of fresh concrete by reducing the thermal or differential cracking in mass concretes by decreasing heat of hydration [2, 3]. Ground Granulated Blast Furnace Slag (GGBS) is a useful by-product obtained from the blast furnace and can be used both as coarse aggregates (un-ground) and supplementary cementitious mater (Ground form) [4]. Fly ash is also waste materials produced from electric arc furnace, and coal-fired power stations resemble pozzolanic characteristics and therefore can be constructively used [5-7]. Using of industrial by-products like GGBS, silica fumes, fly ash and combination of them in concrete, reduces the problem of CO2 which is higher during cement production and eliminates the usage of natural resources like clay, limestone and sand [8-10]. Besides, they also increase the strength by secondary hydration reactions.

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Polymers have been used widely in the construction industry to improve the mechanical performance of mortar and concrete [11, 12]. Styrene-Butadiene Rubber (SBR) latex having characteristics of high-polymer dispersion emulsion and capable of bonding with other materials, is extensively used material in engineering construction. Many types of research have been carried out on concrete incorporating SBR latex [13-15]. In the following paragraph, a brief literature review concerning the use of SBR in cementitious composites is provided.

Shirshova et al. evaluated cement slurry containing 14% SBR by mass of cement: They have reported that in SBR cement paste, a continuous polymer network was formed due to polymer latex, which exhibited negative impact on the compressive strength, while increased strain to failure ratio [16]. Schulze studied the effect of water to cement ratio and cement content on the characteristics of mortars containing polymers: They have reported that the flexure strength of SBR modified mortar increased as the content of the SBR improved up to 20 % and then showed fluctuation [17]. Wu et al. have reported that the water-proofing property of the mortar was greatly enhanced by using SBR [18]. Issa et al. have reported that the SBR polymer-modified concrete could improve the toughness of the overlay concrete [19]. Hadithi et al. studied the effect of fibers reinforcement on polymer-modified concrete and have reported that the addition of polymer in mortar developed better polymer film accompanied with cement and aggregate and showed effective results as compared to that of the conventional mortar [20]. Singh et al. have suggested that workability and mechanical performance like flexural strength; tensile strength can be improved by increasing polymer content [21]. Tchetgnia et al. have described that polymer-modified mortar in different environmental condition revealed effective strength and durability properties as compared to conventional cement mortar [22]. Wang et al. researched the mechanism of polymer latex modified cement and concluded that polymer latex without active groups demonstrated similar physical modification mechanism [23].

The active groups interacted with the hydration products in the process of chemical alteration, binding the polymer latex chains together. Such chemical reactions produced a 3D network structure that enhanced the altered cement's flexural strength. According to Singh et al. and Liu et al., the introduction of SBR significantly changed the concrete and mortar's mechanical and permeability properties [24, 25]. SBR latex consistency depends on both the water-to-cement ratio and the latex percentage. Barluenga et al. are of the view that polymer-modified mortars are associated with a reduction in compressive strength and elastic modulus, improved flexural strength and increased cone permeability [26]. Xin et al. evaluated mortars incorporated with polyester fibers and SBR in terms of mechanical strength [27]; They have reported that the mechanical properties of SBR latex modified mortar depend on dosage parameter. Compressive strength in the first case containing polymer to cement ratio of 15% decreases as the percentage of latex increases and the flexural strength does not depend on the latex percentage. For 10% polymer to cement ratio, compressive strength does not depend on the percentage of latex and improves the flexural strength with latex level. The correlation showed an increase in strength between 28 days and 90 days, which was over 50% for a total polymer content of 20%. Based on the above studies, and numerous others, it can be concluded that the introduction of polymers (SBR) leads to reduction in mechanical strength of the cementitious composites. SBR is normally required to impart adhesive properties, and datasheets recommend to reduce the water content of the mix by an equivalent amount of SBR in order to enhance strength owing to lesser w/c ratio. But cement needs optimum hydration and any scarcity of water might lead to un-hydrated cement particles, which adversely affects the mechanical characteristics of the material. Further, for enhancing the quality of the bond, cement is supplemented with SCMs. The pozzolanic SCMs require hydrated compounds ($Ca(OH)_2$) for secondary hydration and any scarcity of water at primary hydration (due to SBR) might hinder the usefulness of the SCMs at secondary hydration level.

In this study, the effects of SBR and SCMs i.e. Fly ash and Silica Fume as partial replacement of cement on compressive and flexure strength of mortar are investigated. The acquired materials and the standard ASTM methods, used during this study are presented in Materials and Methods section. The test results and materials behaviour are shown in the Results section. As the adhesive properties of SBR are well documented and proven in literature, the focus was fixed on the strength characteristics. Previous studies suggest that SBR-modified cementitious composites exhibit lower mechanical strength. The high strength of cement is mainly associated with C-S-H, and SCMs like silica fumes and fly ash promote the formation of C-S-H [28]. A series of polymer-modified samples, containing SCMs were cast and their strength was compared with that of the control specimen. The effect of SBR and SCMs on the strength of the mortar was confirmed by examining the microstructure of mortar by using scanning electron microscopy/energy dispersive spectrometry (SEM-EDS). The microscopic study (SEM+EDS) clearly diagnosed the reasons for the lower strength of SBR-modified mortars: This is presented in the Discussion section.

2. Materials and Methods

The research methodology is shown in Figure 1. The details of the materials and the methods are presented as follows:

2.1. Cement

Ordinary Type-I Portland cement from Askari cement has been used for mortar compressive and flexure strength. Cement properties are listed in Table 1.

2.2. Sand

The fine aggregate used in this research was obtained from Attock. The physical characteristics of sand are described in Table 2, while the sieve analysis results are shown in Figure 2.

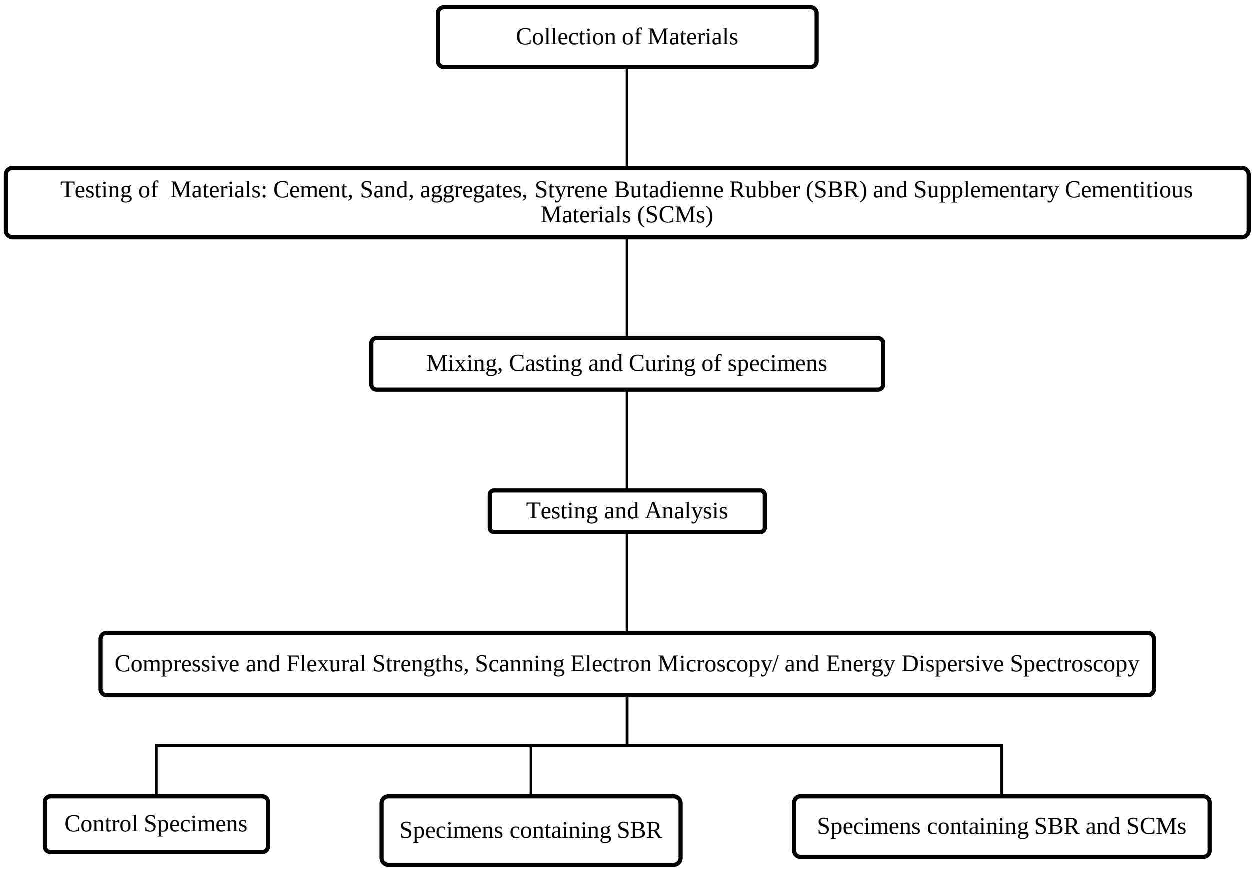


Figure 1. Research Methodology

2.3. SBR Latex

Aquaplast (SBR Waterproofing Admixture) was used for the manufacture of modified mortar. The technical specification of the SBR used is revealed in Table 3.

2.4. Silica Fume

Silica fume from SIKA was incorporated in this research. The physical and chemical properties were listed in Tables 4 and 6.

2.5. Fly Ash

For this research, fly ash collected from the power plant for Hyderabad (Pakistan) was used. Tables 5 and 6 show the physical and chemical properties.

Table 1. Properties of Cement used

Sl. Number	Property		Results
1	Fineness		2.5% by wt.
2	Soundness		1 mm
3	Setting time	Initial	34 min
		Final	380 min
4	Compressive strength		55 N/mm^2
5	Standard consistency		33%
6	Specific Gravity		2.6%

Table 2. Physical Characteristics of Sand

Sl. Number	Property	Sand
1	Specific Gravity	2.68
2	Particle Size	0.25mm
3	Absorption	0.5%

Table 3. Technical specification of SBR

Test Method	Results	Control
Tensile strength	3.3 N/mm^2	2.7 N/m ASTM C-190-85
Flexure strength	9.0 N/mm^2	7.9 N/mm^2 BS 6319, P3:1983
Slant Shear Bond	20.0 N/mm^2	2.6 N/mm^2 BS 6319 Pt4; 1984
Mixed density	1750 kg/m^3	
Application Temp Minimum	50°C	

Table 4. Physical properties of Silica Fume

Sl. Number	Physical properties	Observed values
1	Specific gravity	2.2
2	Bulk density	1400 kg/m^3
3	Fineness	20,000 m^2
4	Particle size	0.1μm (approx.)

Table 5. Physical properties of fly ash

Sl. Number	Physical properties	Observed Values
1	Specific gravity	2.50
2	Initial setting time	45 min
3	Final setting time	281 min
4	Consistency	34%

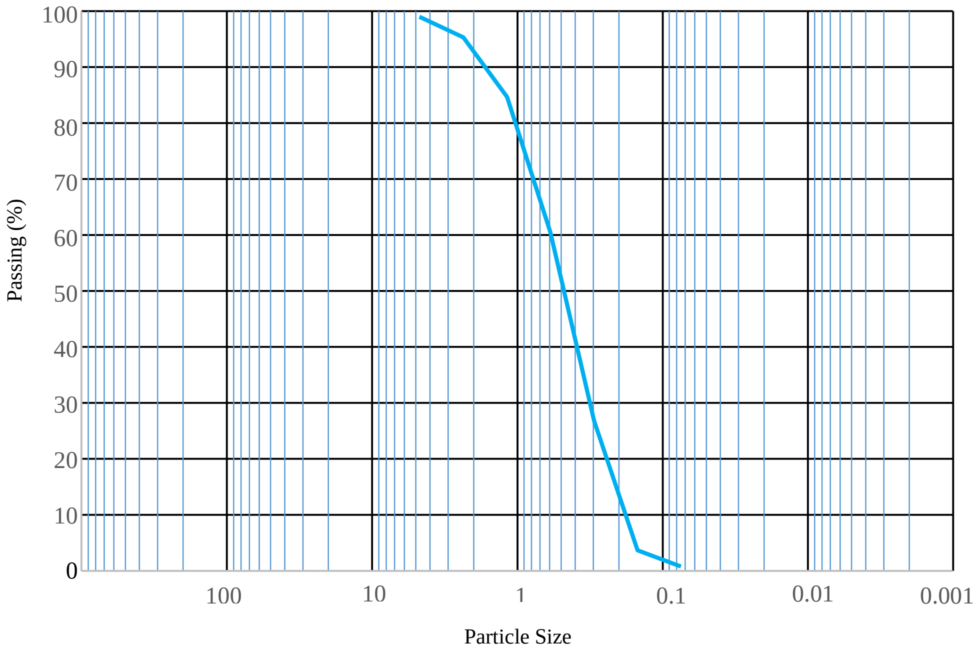


Figure 2. Sieve Analysis results of Sand

Table 6. Chemical properties of cement, Fly ash and silica fume

Chemical compositions %	SiO2	Al2O3	Fe2O3	SO3	CaO	MgO	K2O
Cement	22.8	6.5	2.3	2.7	60.2	1.9	0.54
Fly ash	42.04	23.60	13.40	0.40	12.73	0.98	2.46
Silica fume	96.0	0.1	0.6	-	0.1	0.2	0.4

2.6. Mixture Proportions

The Cement-to-sand mortar samples were cast by weight ratio of 1 to 2.75. The polymer (SBR) was added to the cement mass at a rate of 20 percent as proven by many researchers in the literature that exhibited feasible performance over strength parameters [17, 27]. For control specimens, the water-to-cement ratio (W/C) was kept at 0.5 and the quantity of mixing water in samples containing SBR was decreased by the same quantity as the SBR. Firstly, SBR was introduced pursued by the water by constantly monitoring the consistency of the mix. The control and SBR added specimens were ensured to have the same consistency. Modified mortar samples are casted with 20% fly ash and 2.5% silica fume as a replacement for cement with the same SBR content. Cement and sand were mixed in a regular 30-second laboratory mixer in the mixing process. Water and SBR were added to the mix later, mixing the whole mixture for a minute. Mixing was stopped for a minute after that and then continued for another minute.

Table 7. Design of Mortars

Specimen ID	Cement (g)	Sand (g)	SBR (ml)	Silica fume (g)	Fly Ash (g)	W/C
Mo	493	1350	0	0	0	0.5
M1	493	1350	100	0	0	0.5
M2	382.075	1350	100	12.35	98.6	0.5

2.7. Specimens Preparation

Firstly, the material used to prepare the mortar sample, such as cement, sand, fly ash, SBR and silica fume, was accurately weighed. When the mixture has been prepared, it was placed in the thoroughly cleaned and oiled mold (on the inside face) on the vibrating machine and the mold was filled with the complete quantity of mortar using the appropriate hopper and vibrated it for minutes to achieve complete compaction as shown in Figures 3 and 4.

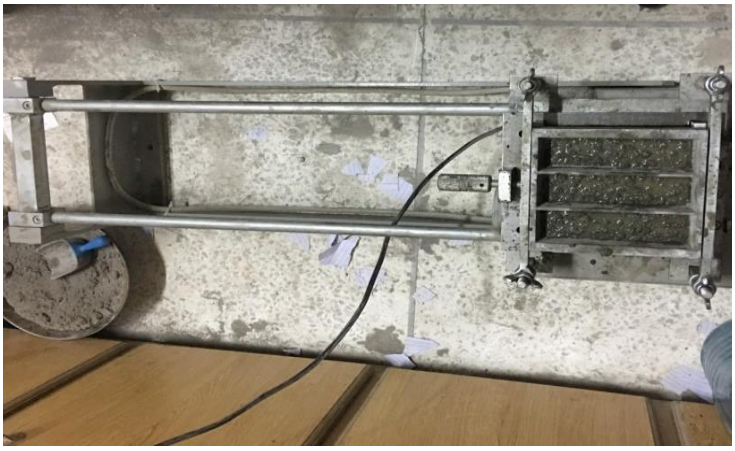


Figure 3. Vibrating machine used for compaction

Figure 4. Casting of Mortar

2.8. Testing Procedure

The compressive test was carried out in accordance with the standards of ASTM C 349 [29]. The sample size was 160x40x40 mm. Before experimenting, the net surface area of the samples was determined. Multifunctional Control Console (MCC) was used for testing as shown in Figure 6 with the least accuracy of 1%. The load was applied in compliance with the requirements until the point of failure reached and the failure load was noted. After that compressive strength of mortar was calculated. For each sample, this analysis was carried out. The compressive strength test was performed at 3, 7 and 28 days of age. Each mix was made of nine cubes. The average of the results obtained from three cubes was the final compressive strength recorded.

The cubes with a size of 40×40×160 mm were casted according to ASTM 348-02 [30]. The samples were demolded after 1day and then cured as shown in Figure 5. The flexure strength test was performed at 3, 7, and 28 days of age. The concluding flexural strength noted was the average of the result attained from three cubes.

Figure 5. Curing of samples

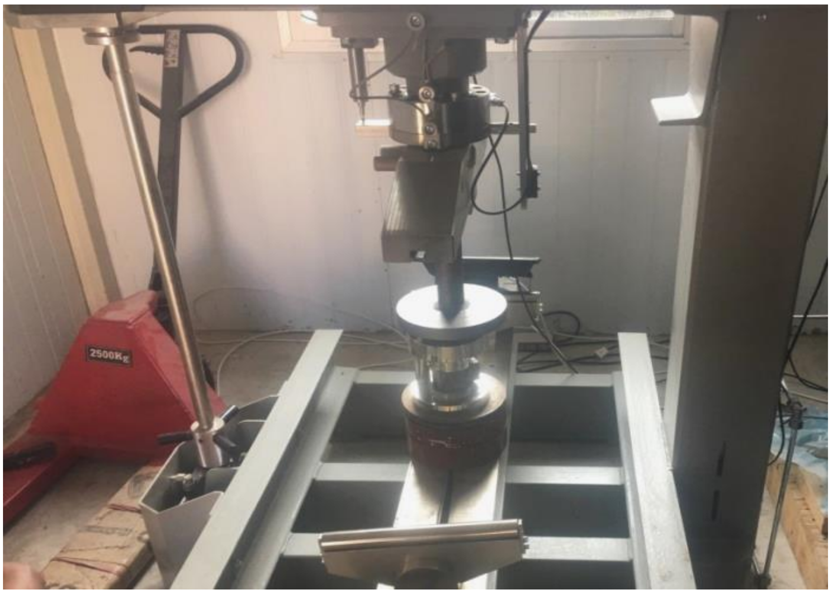


Figure 6. Multifunctional Control Console (MCC) machine

3. Results and Discussion

3.1. Compressive and Flexure Strength Results

Table 7 shows the compressive strength of the tested mortar specimens. Test results showed that there was greater compressive strength of the control specimen without the addition of SBR and admixture. For mortar specimens incorporating 20 percent SBR, 2.5 percent Silica fume, 20 percent fly ash, approximately 42% reduction in compressive strength compared to control specimen was observed as shown in Figure 7. There was also a decreasing trend when Mo was compared with M1, where compressive strength decreased by up to 44 percent as shown in Figure 7. Control mortar specimens showed a compressive strength of 15.5, 25.5 and 27.34 MPa, for 3, 7 and 28 days correspondingly. The compressive strength of 8.4, 10.46 and 12.17 MPa had been shown for 20 percent replacement of SBR. Similarly, there was compressive strength of 9.3MPa, 9.43MPa and 11.52Mpa for mortar samples with 20 percent SBR, 2.5 percent Silica fume, and 20 percent fly ash. Therefore, it can be concluded that the compressive strength shows decreasing trend after adding admixture and SBR.

Approximately 70 percent decrease in flexure strength was observed for mortar as shown in Figure 8, when specimens containing 20 percent of SBR were compared to the sample without SBR for 28 days. As M2 was compared with Mo, a 61 percent reduction in flexure strength was observed. 20 percent replacement of SBR showed flexure strength of 3.81 MPa, 3.8 and 4.5, Likewise SBR modified mortar with admixtures had shown 2.68, 3.37 and 3.94 MPa respectively as shown in Table 8.

Table 7. Comparison of compressive strength of control and modified mortar

S. NO	Comp strength 7 days	Comp strength 14 days	Comp strength 28 days
M0	15.5	25.2	27.34
M1	8.4	10.46	12.17
M2	9.3	9.43	11.52

Table 8. Comparison of flexure strength of control and modified mortar

S. NO	flexure strength 7 days	flexure strength 14 days	Flexure strength 28 days
M0	4.91	5.48	6.46
M1	3.81	3.8	4.5
M2	2.68	3.37	3.94

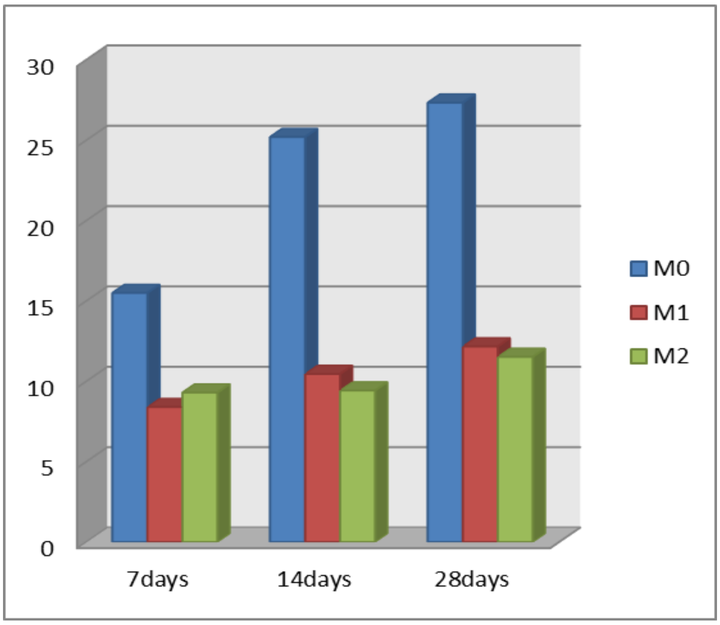


Figure 7. Comparison of compressive strength of control and modified mortar

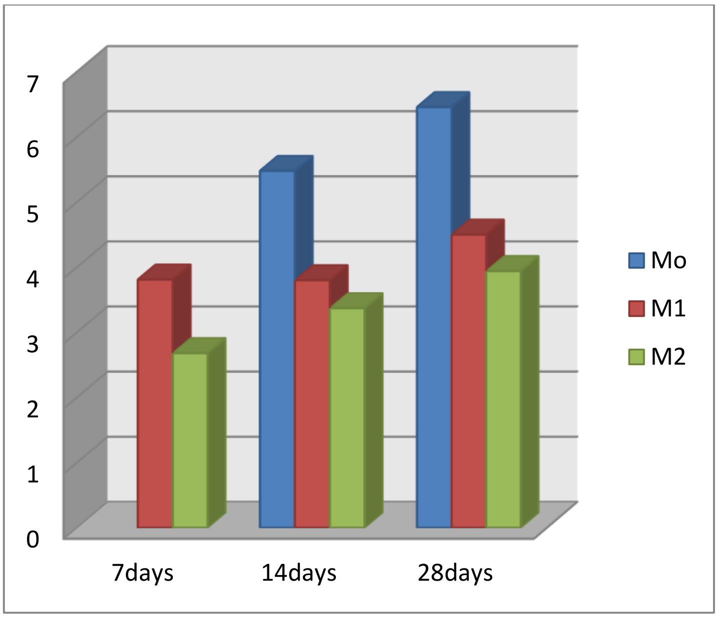


Figure 8. Comparison of flexure strength of control and modified mortar

3.2. SEM Analysis

The high strength of cement is mainly associated with C-S-H. The structure of C-S-H could be studied by X-ray and electronic microscope. C-S-H elements are not adequately crystallized according to the studies; even they have a characteristic closeness to amorphous structure in nature. These elements mostly differ in the form of fibers and thin plates. A hexagonal crystalline Ca $(OH)_2$ is formed by the generation of hydrated units of calcium silicate, which acts as a bridge between hydrated units. The increase in C-S-H units in time enhances the size of fibers and plates to enter and merge each other. As a result, the increase in strength of cement in time happens [31, 32].

To investigate the influence of SBR, fly ash and silica fume on the mechanical properties of mortar, the morphology of control and modified mortar at the phase of 28days were observed by SEM. The results are shown in the Figures 9 to 11. The hydration products, calcium silicate hydrate (C-S-H), Wollastonite, and CaCO3, of some of the samples, were easily visible after 28 days of curing in water. It is once again iterated that Mo corresponds to the control specimens, while M1 and M2 correspond to the specimens with SBR only, and SBR with silica fumes and fly ash respectively. The control specimens as shown in Figure 11(a, b, c) are characterized by the formation of Albite and K-Feldspar in hydrated form. The following hydration reactions are responsible for the formation of Albite and K Feldspar:

$Na_2O+Al_2O_3+3SiO_2 \rightarrow 2NaAlsi_3O_8$ (Albite)

$K_2O+Al_2O_3+3SiO_2 \rightarrow 2KAlSi_3O_8$ (Feldspar)

On the other hand, there is a significant formation of Wollastonite ($CaSiO_3$). Wollastonite is formed as a solid phase reaction of $CaCO_3$ with silica fume (or smoke): This compound is shown as a white cooler phase in the Scanning electron microscopic view, shown in Figure 11(a, b, c) below M2 specimens. Figure 10(a, b, c) reveals that a little scattered polymer film formed. The ingredients of paste are loosely joined and the mortars exhibit penetrating structure. Moreover, the high percentage of SBR affects the cement hydration process that results in loss of strength.

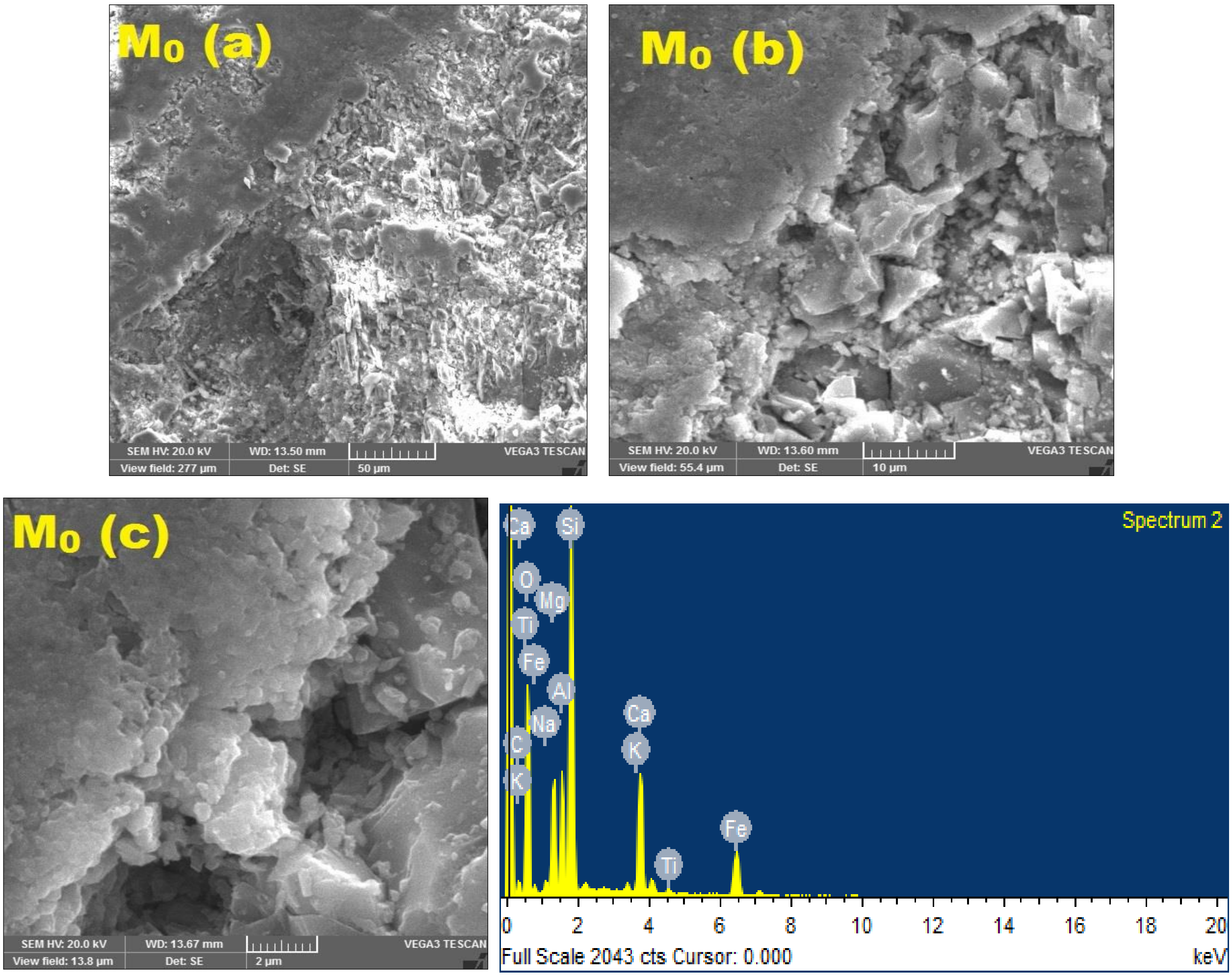
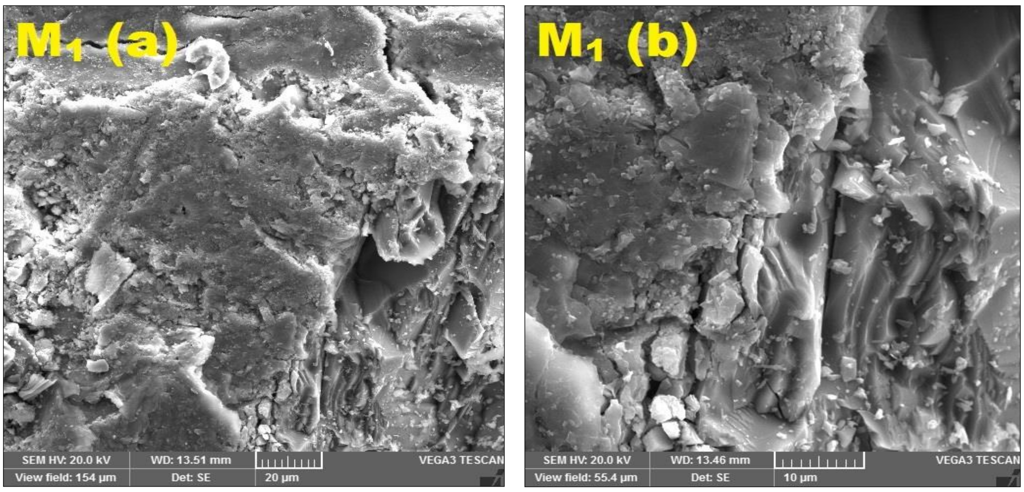


Figure 9 (a, b and c). SEM and EDS images for control mortar at the age 28days



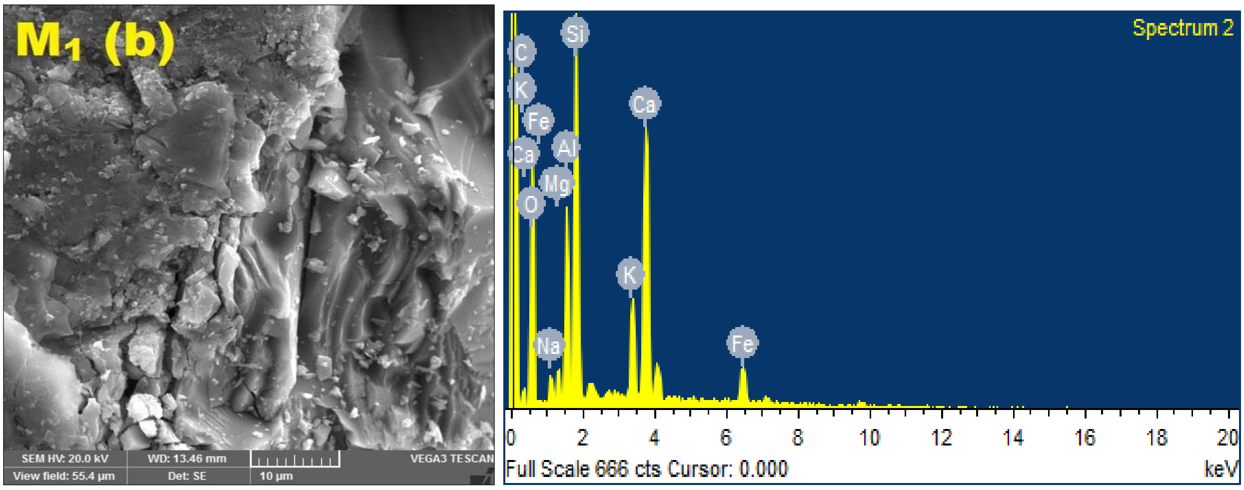


Figure 10(a, b and c). SEM and EDS images for SBR modified mortar at the age 28days

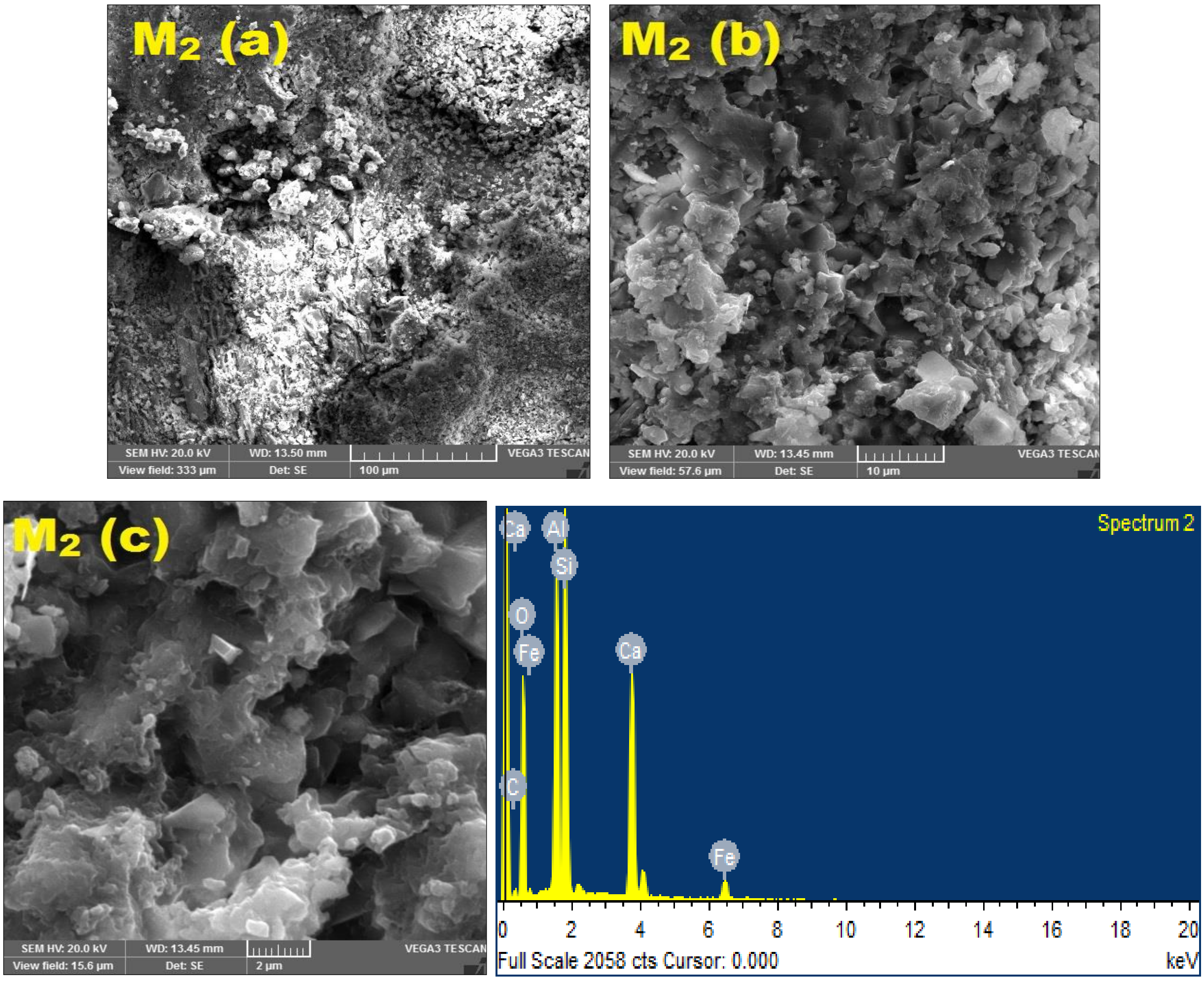


Figure 11(a, b and c). SEM and EDS images for SBR, Silica Fume and Fly Ash mortar at the age 28days

3.3. EDS Results

EDS stands for Energy Dispersive Spectroscopy. This technique identifies the particular elements and their relative proportions (Atomic % for example). The summary of the results is presented in the Table 9.

Table 9. EDS Result

Elements	Form	M0		M1		M2	
		% weight	% atomic	% weight	% atomic	% weight	% atomic
C	CaCO3	5.82	9.12	20.9	30.7	9.32	15.54
O	SiO2	57.3	67.4	41.5	45.8	49.2	61.56
Na	Albite (NaAlSi3O8)	0.76	0.62				
Al	Al2O3	7.04	0.62			1.38	1.02
Si	SiO2	20.8	14	36.9	23.2	8.13	5.8
K	Feldspar (KAlSi3O8)	8.24	3.97				
Mg	MgO					0.37	0.31
S	FeS2					0.6	0.38
Ca	CaSiO3			0.78	0.35	30.3	15.16
Fe	Fe					0.68	0.25
Total		100	100	100	100	100	100

4. Discussion

It has been observed that with the addition of SBR (M1) and SBR, silica fume, fly ash (M2) in various proportions as a replacement for the cement and water, the compressive strength and flexure strength decreased when compared to the specimen without replacement (i.e. Mo). Normally, the datasheets of SBR suggest to reduce water content of cementitious materials by an equivalent amount of SBR for the sake of same consistency: While it makes the cementitious composites harder and adhesive, it might also reduce the necessary water content needed for hydration. It is clear from the above study that SBR if used as a replacement of water in a cement mortar, leads to the reduction of its strength. The strength gets further reduced if silica fumes and fly ash are added. For mortar specimens M1 (i.e. containing only SBR), the strength decreases since 20% water were replaced by SBR; the cement could not get enough water for its hydration. As the hydration did not complete, the strength also decreased. For mortar specimens M2 (i.e. containing SBR as well as Silica fumes and fly ash), there is no improvement in the strength. Silica fumes and fly ash are very fine particles; they need even more water for lubrication and hydration, which is already scarce due to its replacement by SBR. As SEM/EDS studies revealed that excessive formation of Wollastonite happened during the reaction process. Wollastonite was formed as a result of a reaction between CaCO3 and a high percentage of SiO2 in silica fume as well as in Fly Ash. The addition of silica fumes and fly ash is intended to increase the CSH content, as revealed by various past studies [33, 34]. CSH is the key binding phase of cement, and thus the strength of a cementitious composites depends upon its content. CSH is the outcome of the reaction between the silicate phase of cement and water and is normally described by the following equation [35]:

$Ca_2SiO_5+H_2O \rightarrow CaO\text{-}SiO_2\text{-}H_2O$ (CSH)

$Ca_3SiO5+H_2O \rightarrow CaO\text{-}SiO_2\text{-}H_2O$ (CSH)$+Ca(OH)_2$ (Portlandite)

On the other hand, the formation of Wollastonite is a reaction between calcium and silicate phases and is shown as follows [36]:

$CaCO_3+SiO_2 \rightarrow CaSiO_3$(Wollastonite)$+CO_2$

The EDS results shown in Table 9 also indicate higher percentages of $CaCO_3$, and SiO_2 in M2. The formation of Wollastonite had a negative impact on strength parameters by increasing the surface area which leads to an increase in the water demand for cementitious materials [2]. The matrix did not have an adequate quantity of water for hydration leading to a decrease in its strength. There is a need to readjust the water quantity, once the basic composition (i.e. control) is added with SBR or SBR plus SF plus FA.

5. Conclusions

- The test results show that adding SBR to the mortar matrix adversely affects the compressive and flexural strength of the hardened mortar specimens. For silica fumes and fly ash, the strength is further reduced. This is attributed to insufficient formation of CSH and CH. The lesser quantity of CSH reduces strength and that of CH makes the SCMs less effective. The success of SCMs is largely dependent on primary hydration products.
- At maturity (i.e. 28 days), the flexure strength reduces to 70% of control specimen for SBR containing mortar; whereas the flexure strength reduces to 61% of control specimen for SBR containing fly ash and silica fume.
- The compressive strength for 28 days reduces to 44% of control specimen for SBR containing mortar; whereas for mortar incorporating fly ash and silica fume, compressive strength reduces to 42% to that of control mortar.

- The EDS study reveals that no albite is formed in SBR mortar and mortar mixed with fly ash and silica fume. The SiO2 content in M2 and M3 is being utilized in the formation of Wollastonite which is responsible for lower strength. The formation of Wollastonite also reveals that the SBR hinders the formation of hydration products (CSH and CH).
- To regain the loss of strength due to lesser water available for hydration, a superplasticizer is recommended for future studies.
- There is a need to study the mortar properties at lower SBR proportions. A future study with a varying polymer to cement ratio can be carried out to find an optimum value of polymer for a mortar specimen.
- The water quantity should also be adjusted if SBR is added to a cement mortar so that its cementitious ingredients get sufficiently hydrated.

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7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Khitab,A. Materials of Construction. Allied Books (2012).

[2] Neville,A.M. “Properties of Concrete Fourth and Final Edition.” In Perason-Prentice Hall (2004).

[3] Khitab,A., and Anwar,W. “Classical Building Materials.” In Advanced Research on Nanotechnology for Civil Engineering Applications (2016): 1–27.

[4] Jalil, Affan, Anwar Khitab, Hamza Ishtiaq, Syed Hassan Bukhari, Muhammad Tausif Arshad, and Waqas Anwar. “Evaluation of Steel Industrial Slag as Partial Replacement of Cement in Concrete.” Civil Engineering Journal 5, no. 1 (January 27, 2019): 181-190. doi:10.28991/cej-2019-03091236.

[5] Khitab,A., Arshad,M.T., Awan,F.M., and Khan,I. “Development of an Acid Resistant Concrete: A Review.” International Journal of Sustainable Construction Engineering and Technology. 4 (2013): 33–38.

[6] Hou, Peng-kun, Shiho Kawashima, Ke-jin Wang, David J. Corr, Jue-shi Qian, and Surendra P. Shah. “Effects of Colloidal Nanosilica on Rheological and Mechanical Properties of Fly Ash–cement Mortar.” Cement and Concrete Composites 35, no. 1 (January 2013): 12–22. doi:10.1016/j.cemconcomp.2012.08.027.

[7] Jo, Byung-Wan, Chang-Hyun Kim, Ghi-ho Tae, and Jong-Bin Park. “Characteristics of Cement Mortar with Nano-SiO2 Particles.” Construction and Building Materials 21, no. 6 (June 2007): 1351–1355. doi:10.1016/j.conbuildmat.2005.12.020.

[8] Asad, Mehwish, Ayub Elahi, Huma Pervaiz, Usman Ali Naeem, Sidra Iftekhar, Muhammad Bilal Asif, Amber Taseer, Ayyaz Tajammal Mirza, and Naeem Ejaz. "Role of Supplementary Cementitious Materials in enhancing Concrete Properties." Life Science Journal 10, no. 12s (2013): 956–960.

[9] Gartner, Ellis. “Industrially Interesting Approaches to ‘low-CO2’ Cements.” Cement and Concrete Research 34, no. 9 (September 2004): 1489–1498. doi:10.1016/j.cemconres.2004.01.021.

[10] Huntzinger, Deborah N., and Thomas D. Eatmon. “A Life-Cycle Assessment of Portland Cement Manufacturing: Comparing the Traditional Process with Alternative Technologies.” Journal of Cleaner Production 17, no. 7 (May 2009): 668–675. doi:10.1016/j.jclepro.2008.04.007.

[11] Vipulanandan, C., and E. Paul. "Characterization of polyester polymer and polymer concrete." Journal of Materials in Civil Engineering 5, no. 1 (1993): 62-82. doi:10.1061/(ASCE)0899-1561(1993)5:1(62).

[12] Rossignolo, João A., and Marcos V.C. Agnesini. “Durability of Polymer-Modified Lightweight Aggregate Concrete.” Cement and Concrete Composites 26, no. 4 (May 2004): 375–380. doi:10.1016/s0958-9465(03)00022-2.

[13] Sakai, Etsuo, and Jun Sugita. “Composite Mechanism of Polymer Modified Cement.” Cement and Concrete Research 25, no. 1 (January 1995): 127–135. doi:10.1016/0008-8846(94)00120-n.

[14] Ollitrault-Fichet, R., C. Gauthier, G. Clamen, and P. Boch. “Microstructural Aspects in a Polymer-Modified Cement.” Cement and Concrete Research 28, no. 12 (December 1998): 1687–1693. doi:10.1016/s0008-8846(98)00153-7.

[15] Kim. “Influence of Polymer Types on the Mechanical Properties of Polymer-Modified Cement Mortars.” Applied Sciences 10, no. 3 (February 5, 2020): 1061. doi:10.3390/app10031061.

[16] Shirshova, Natasha, Angelika Menner, Gary P. Funkhouser, and Alexander Bismarck. "Polymerised High Internal Phase Emulsion Cement Hybrids: Macroporous Polymer Scaffolds for Setting Cements." Cement and Concrete Research 41, no. 4 (April 2011): 443–450. doi:10.1016/j.cemconres.2011.01.017.

[17] Schulze, Joachim. "Influence of Water-Cement Ratio and Cement Content on the Properties of Polymer-Modified Mortars." Cement and Concrete Research 29, no. 6 (June 1999): 909–915. doi:10.1016/s0008-8846(99)00060-5.

[18] Wu, Ke-Ru, Dong Zhang, and Jun-Mei Song. "Properties of Polymer-Modified Cement Mortar Using Pre-Enveloping Method." Cement and Concrete Research 32, no. 3 (March 2002): 425–429. doi:10.1016/s0008-8846(01)00697-4.

[19] Issa, Mohsen A., Mohammad A. Alhassan, and Hameed Shabila. "High-performance plain and fibrous latex-modified and microsilica concrete overlays." Journal of materials in civil engineering 20, no. 12 (2008): 742-753. doi:10.1061/(ASCE)0899-1561(2008)20:12(742).

[20] A.Al-Hadithi,A.I., and Al-Kubaysi,G.S.J. "Improving the Mechanical Properties of Steel Fiber Concrete by using Acrylic Polymer." The Iraqi Journal for Mechanical and Material Engineering. Special Is (2010): 46–51.

[21] Singh, S.B., Pankaj Munjal, and Nikesh Thammishetti. "Role of Water/cement Ratio on Strength Development of Cement Mortar." Journal of Building Engineering 4 (December 2015): 94–100. doi:10.1016/j.jobe.2015.09.003.

[22] Tchetgnia Ngassam, Inès Leana, Sandrine Marceau, and Thierry Chaussadent. "Durability of Polymer Modified Repair Mortars on Concrete Structures." Advanced Materials Research 687 (April 2013): 397–402. doi:10.4028/www.scientific.net/amr.687.397.

[23] Wang, Min, Rumin Wang, Hao Yao, Shameel Farhan, Shuirong Zheng, Zhujun Wang, Congcong Du, and Hao Jiang. "Research on the Mechanism of Polymer Latex Modified Cement." Construction and Building Materials 111 (May 2016): 710–718. doi:10.1016/j.conbuildmat.2016.02.117.

[24] Singh, Manisha, Jignesh Goswami, and Rabin Santra. "Effect of Styrene Butadiene Ratio on Mechanical Properties of Concrete Mixture." Polymer-Plastics Technology and Engineering 51, no. 13 (September 2012): 1334–1339. doi:10.1080/03602559.2012.702251.

[25] Liu, Jun, Yun Zhang, Runqing Liu, and Bing Zhang. "Effect of Fly Ash and Silica Fume on Hydration Rate of Cement Pastes and Strength of Mortars." Journal of Wuhan University of Technology-Mater. Sci. Ed. 29, no. 6 (December 2014): 1225–1228. doi:10.1007/s11595-014-1072-7.

[26] Barluenga, G., and F. Hernández-Olivares. "SBR Latex Modified Mortar Rheology and Mechanical Behaviour." Cement and Concrete Research 34, no. 3 (March 2004): 527–535. doi:10.1016/j.cemconres.2003.09.006.

[27] Xin, Deng, Zhu Xinping, Chen Hanlin, Wang Dingpeng, and Yin Wei. "Mechanical properties of polyester fiber and sbr latex compound-modified mortar for tunnel grouting." Electronic Journal of Geotechnical Engineering 21, no. 4 (2016): 1365-1374.

[28] Numan, Hesham A., Mohammed Hazim Yaseen, and Hussein A. M. S. Al-Juboori. "Comparison Mechanical Properties of Two Types of Light Weight Aggregate Concrete." Civil Engineering Journal 5, no. 5 (May 21, 2019): 1105–1118. doi:10.28991/cej-2019-03091315.

[29] ASTM C349-18. Standard Test Method for Compressive Strength of Hydraulic-Cement Mortars (Using Portions of Prisms Broken in Flexure). West Conshohocken, PA (2018).

[30] ASTM C348-19. Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. West Conshohocken, PA (2019).

[31] Richardson, I. G., and G. W. Groves. "Microstructure and Microanalysis of Hardened Ordinary Portland Cement Pastes." Journal of Materials Science 28, no. 1 (1993): 265–277. doi:10.1007/bf00349061.

[32] Scrivener,K., Snellings,R., and Lothenbach,B. A Practical Guide to Microstructural Analysis of Cementitious Materials. Eds: Scrivener K, Snellings R, and Lothenbach B CRC Press (2018).

[33] Mohamed, Heba A. "Effect of Fly Ash and Silica Fume on Compressive Strength of Self-Compacting Concrete under Different Curing Conditions." Ain Shams Engineering Journal 2, no. 2 (June 2011): 79–86. doi:10.1016/j.asej.2011.06.001.

[34] Thomas, M. D. A. Optimizing the use of Fly Ash in Concrete. Vol. 5420. Skokie, IL: Portland Cement Association, (2007).

[35] Harrisson, Arthur Michael. "Constitution and Specification of Portland Cement." Lea's Chemistry of Cement and Concrete (2019): 87–155.

[36] Zhu, Hui, R. C. Newton, and O. J. Kleppa. "Enthalpy of formation of wollastonite (CaSiO3) and anorthite (CaAl2Si2O8) by experimental phase equilibrium measurements and high-temperature solution colorimetry." American Mineralogist 79, no. 1-2 (1994): 134-144.