Enhancing the plastic and hardened including the bonding strength cement mortar modified with polycarboxylate superplasticizer

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Abstract

In this study, the effect of different types of polymer on the fluidity, consistency, setting time, density and mechanical properties of cement mortar were investigated. Three types of polymer with the different percentage up to 0.25 % (by dry weight of cement) were used. The effect of polymers on the compressive and flexural strengths of hardened cement mortar for 1, 3, 7 and 28 days of curing were also studied. Additional of 0.20 % of polymers to the cement mortar increased the compressive strength by 197 % to 230 % based on the types of polymer, water to cement ratio (w/c) and curing time. Additional of 0.25 % of polymers increased the bonding strength of cement mortar by 45% to 168% based on the types of polymer and curing time. Regression analysis was used to separate the effect polymers, w/c and curing time on the compressive strength of cement mortar. The Vipulanandan correlation model was used to correlate the polymer content with the compressive strength and the flexural with compressive strengths of cement mortar modified with different types of polymer. Addition of polymers to the cement mortar increasing the workability and the compressive for different curing time.

1. Introduction

The mortar is a composite material consisting of a mixture of cementitious material (cement), fine aggregates (sand), an amount of water required for hydration reactions [1-3]. Compressive strength and workability are the most important property of hardened and fresh cement mortar that describes its quality and performance for construction works. Also, most of the other properties such as flexural, shear and bonding strength were improved in parallel with the increase in compressive strength [4-13].

The workability is an important plastic property of cement mortar. It must be free flowing without the segregation of solid materials or water in the mix [4]. The workability of cement mortar influenced by the state of dispersion through trapping water in the agglomerate which does not contribute to the flow properties [1]. [14] investigated the influence of sand grading and w/c ratio on the workability and compressive strength of cement mortar. Increasing the w/c ratio reduced the mechanical properties and increased the workability. According to the standard EN196-1 the water to cement ratio of cement paste and cement mortar is 0.5 [15].

Mineral admixtures, such as fly ash, lime, and silica fume have been used in a high range as a replacement of cement to improve the properties of cement mortar. [16] investigated the effect of lime and fly ash up to 35% on the mechanical properties of cement mortar, although the high percentage of additives such as lime, fly ash and silica fume were used the compressive and flexural strengths were decreased by 3% to 86% based on the type of additives and curing time. [17] tested the effect of six different fineness of 40% of fly ash on the compressive strength of cement mortar up to 90 days of curing, with 40% of additives no improvement in the compressive strength was observed. The cement mortar required more water than cement paste in the long-term for its hydration; thus the excess water evaporated and leaving voids on the cement mortar [2].

Adding small quantities of polymeric admixture to cement mortar reduce the amount of water that required to achieving the desired workability [18]. The polymeric admixtures are used to modify the cement and mortar by accelerator or delay the setting time according to the desired project in order to the to improve the physical properties and mechanical properties of cement mortar and concrete in the fresh cement paste and hardened state [19,20]. The addition of polymeric admixtures to the cement mortar optimize the fluidity and strength properties by creating an electrostatic repulsion and/or stress, which causes a deflocculating [6].

In this study, the effect of three types of polymer on the workability, consistency, setting times, density and mechanical properties of cement mortar were studied and quantified.

1.1 Objectives

The overall objective of this study is to investigate the effect of three types of polymer on the plastic and hardened properties of cement mortar. The specific goals are as follows:

(i) To investigate the impact of different types of polymer on the setting time, flowability and the density of cement mortar.

(ii) Developing a non-linear relationship to evaluating the effect of w/c, curing time and polymer content on the compressive strength of cement mortar.

(iii) Investigate the effect of polymers on the tensile bonding strength of cement mortar

(iv) To quantify the relationship between the compression and flexural strengths of cement mortar up to 28 days of curing.

2. Materials and Methods

2.1 Cement

The type of cement used in this study was ordinary Portland cement (OPC) from the Gasin Cement Company (Iraq, Kurdistan-Region, Sulaymaniyah City, 35°33′26″N 45°26′08″E). The chemical compositions of the cement used are summarized in Table 1 .

Table 1 Chemical composition for Gasin Ordinary Portland Cement

Chemical composition	Chemical formula	Chemical content (%)
Lime	CaO	63.9
Silica	SiO_2	20.1
Alumina	Al_2O_3	4.08
Ferrite	Fe_2O_3	5.10
Magnesia	MgO	1.46
Sulfur trioxide	SO_3	2.20
Loss on ignition	LOI	3.41

2.2 Polymers

In this study, three types of water reducing polymer (Synthetic powder) were used. The commercial name the three polymers are RT-03 (Polymer A), DBC-21(Polymer B) and VK-98 (Polymer C). The properties of the three types of polymer are summarized in Table .

Table 2 The properties of powder polymers used in this study

Polymer	A	B	C
Commercial Name	RT-03	DBC-21	VK-98
Solid Content (%)	98±1	> 97	> 97
pH Value	7-9	6-8	9-11
Water Reduction (%)	>25	>25	>25
Air Content (%)	=< 3	< 3	< 3
Chloridion (%)	< 0.1	< 0.1	< 0.1
Alkali (%)	< 5	< 4	< 5

2.3 Water

Tap water was used in this study.

2.4 Sand

The CEN standard sand was used in this study which well graded rounded particles were having a silica content of 98 % as specified in EN196-1 standard requirements [21, 22]. The standard sand was delivered in plastic bags with a content of 1350 g.

2.5 Methodology

All the tests were performed based on ASTM and BS standards. At least three samples were tested for each condition.

2.5.1 Standard consistency test (BS EN 196-3:2016)

This test aims to determine the minimum quantity of mixing water to the initial chemical reaction between water and cement. Cement is one of the materials which the right amount of water leads to attaining required cement strength. The standard consistency was carried out according to the EN196-3 standard using the Vicat apparatus. The cement paste was prepared by putting 500 g of cement into the bowl of the mixer. The amount of water is added to the cement. The mixing was left for 10 seconds for absorption. Then the mixing apparatus was put at a low speed for 90 seconds then stooped the mixture for 30 seconds to bring the cement that located beyond the mixing zone. After that, the mixer restarted at a low speed for 90 seconds. Without excessive compaction or vibration, the paste is quickly put into the mould which is placed on a glass plate and placed on the plate of the Vicat apparatus. The cement consistency which will allow the Vicat plunger to penetrate to 6 ± 2 mm point from the bottom of Vicat mould is known as standard consistency [23-26]. The same procedure was repeated when the polymers were added to the cement. Addition of polymers reducing the necessary water to reach the standard consistency as shown in Fig.1.

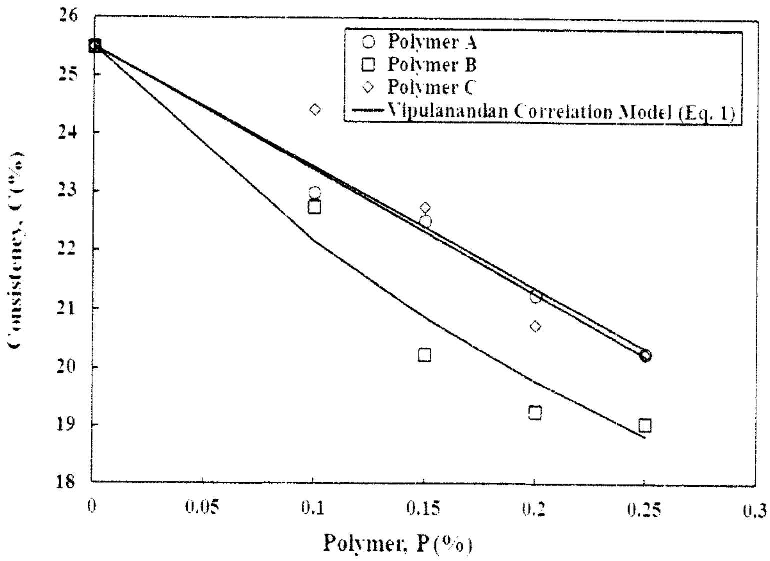


Fig.1 Relationship between consistency of cement paste and polymer content

2.5.2 Setting time test (BS EN 196-3:2016)

The setting time was determined by observing the penetration of a needle into a standard consistency cement paste until it reaches a specified value. It is necessary to evaluate the setting time of the hydraulic binders to regulate the time available for the in situ application of mortars. Setting time is measured using the Vicat apparatus. Generally, Initial setting is the time elapsed between the moment water is added to the cement to the time at which paste starts losing its plasticity. The final setting time of cement is the time elapsed between the moment the water is added to the cement to the time at which paste has completely lost its plasticity and attained sufficient firmness to resist certain definite pressure.

2.5.3 Cement mortar preparation (BS EN 196-1:2016)

After mixing, the mortar filled a cubic mould with a dimension of (4 x 4 x 16) cm3. The mortar put into the mould in two layers and by applying to the mould 60 shocks each time using the shock device. After that the mould is levelled and covered with a plastic bag and stored in the room temperature. After 24 h from the of the mixing procedure, the specimens removed from the mould and stored in water at 25°C ± 2°C and 95% of humidity, until the time of the test of the sample. The samples for compressive strength were tested at 1, 3, 7 and 28 days. Bending test machine with a rate of 0.05 MPa/sec was used to break the specimen into two parts and each part was subjected to the compressive strength with a rate 0.2 MPa/sec using a hydraulic compressive testing machine. The water reduced to remain the flowability in the range of 105 % to 115 % as recommended by ASTM C109.

2.5.4 Flowability (ASTM C1437)

The flowability of cement mortar was determined by using the flow table method as described in ASTM C-1437. After mixing the cement mortar the mixing material was placed in the mould in two layers. Each layer was compacted 25 blows using the rod during the 15 sec. The fluidity of the cement mortar was kept in the range of 105 % to 115 % as recommended by ASTM standard. The result of the flow of cement mortar modified with a different percentage of the polymer is shown in Fig.2.

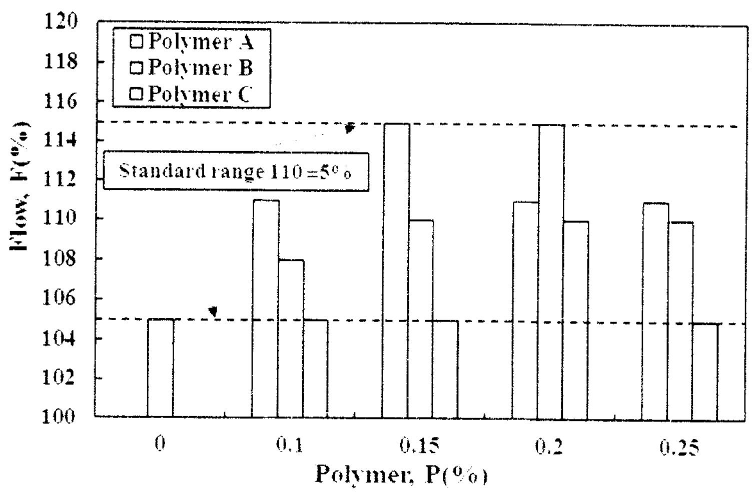


Fig.2 Variation of the flowability of cement paste and polymer content

2.5.5 Tensile bonding strength (CIGMAT CT-3, modified ASTM C321)

Sandwiched samples were prepared to study the bonding strength according to CIGMAT CT-3 standard [27-29]. Concrete bricks were bonded with cement mortar modified with 0.25% of polymers and were cured at 3 and 7 days. The concrete brick was marked to ensure that the crossed concrete brick is placed in middle and at the right angle to each other. The second brick was placed on the mortar and the oriented correctly. The specimens were allowed to cure at room condition 25± 2^0C and 95% of humidity till the time of the test. Specimens were tested by subjecting to tensile loading with a rate of 0.05 MPa/sec as shown in Fig.3. One brick was held by stationary jaws while the other brick was pushed by moving jaws creating a bond force on the bonding. Different type and shape of failure were proposed by CIGMAT CT-3 as summarized in Table. 3.

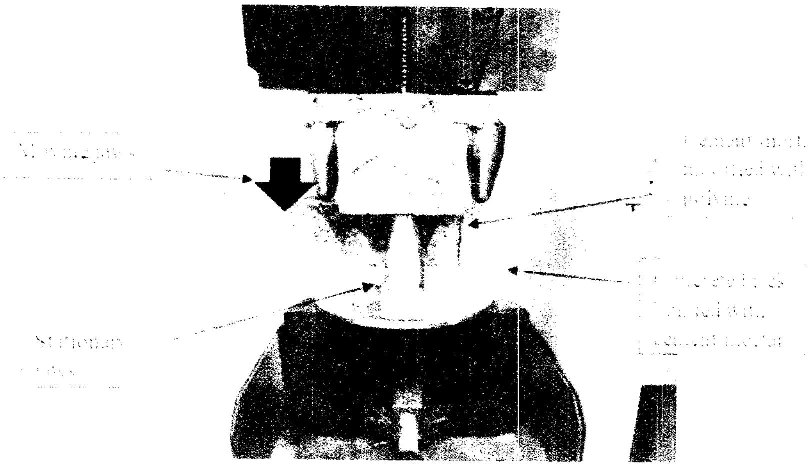
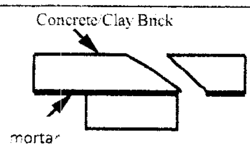
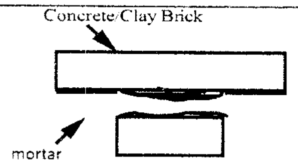
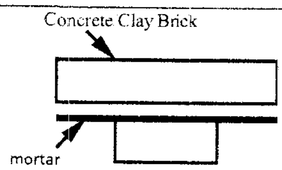
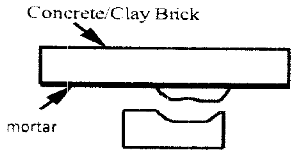
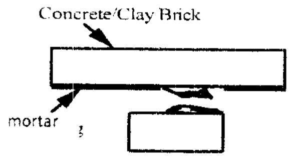


Fig.3 Cement mortar modified with polymer under tensile bonding load

Table 3. Failure Types according to CIGMAT CT 3 standard [27,29]

Failure Type	Description	CIGMAT CT 3 Test
Type 1	Substrate Failure	
Type 2	Mortar Failure	

Type 3	Bonding Failure	
Type 4	Bonding and Substrate Failure	
Type 5	Bonding and Mortar Failure	

2.6 Modelling

2.6.1 Vipulanandan correlation model

Nonlinear relationships between the compressive strength, water reducing and water to cement ratio with polymers content was performed using the Vipulanandan correlation model [23, 24, 30-38]. The model was proposed as follows:

$$Y = Y_o + \frac{X}{(I + H * X)} \quad (1)$$

Where:

Y = Cement mortar property (dependent variable, i.e. fluidity or compressive strength or flexural strength)

Y_o, I and H = model parameters (Table 4 and Table 5)

X = polymer content (P %).

2.6.2 Nonlinear model (NLM)

The compressive strength (σ_c) of cement mortar modified with different types of the polymer was influenced by the curing time (t), water to cement ratio (w/c %) and the polymer content (P (%)) [30-35, 39]. The effects of P (%), t (day) and w/c (%) of the cement mortar were separated as follows:

Compressive strength (σ_c) of cement mortar modified with polymer

$$\sigma_c = a\,(w/c)^{b}(t)^{c} + d\,(w/c)^{e}(t)^{f}(P_A)^{g} \quad 2(a)$$

$$\sigma_c = a\,(w/c)^{b}(t)^{c} + d\,(w/c)^{e}(t)^{f}(P_B)^{g} \quad 2(b)$$

$$\sigma_c = a\,(w/c)^{b}(t)^{c} + d\,(w/c)^{e}(t)^{f}(P_C)^{g} \quad 2(c)$$

Based on experimental data the correlation parameters (a, b, c, d, e, f, and g) were obtained using multiple regression analysis using the least square method as summarized in Table 6.

3. Results and analyses

3.1 Setting time

Additional of polymers to the cement increased the setting time by 10% to 87% based on the setting times (initial or final) and polymer content as shown in Fig.4 and Fig.5. There are several reasons for increasing the setting time of cement with the addition of polymers. With the addition of water, the calcium and hydroxyl ions were released to the surface of cement particles. When the critical value of the concentration of these ions was reached the hydration products Dicalcium silicates (C2S), and Tricalcium silicates (C3S) begin to crystallize. When the polymer reacts with one or more component of the cement to form a precipitate on the surface of the cement particle. The precipitate form gives a low permeability coating on the surface of cement particle. Then the polymer forms a complex with Ca^{+2} ions which are released by hydration. Finally, the polymer poisons the nucleation sites of Ca(OH)2 and/or CSH and stopped the formation of bonds between the hydrated products. In this way, hydration is delayed [1, 18, 40].

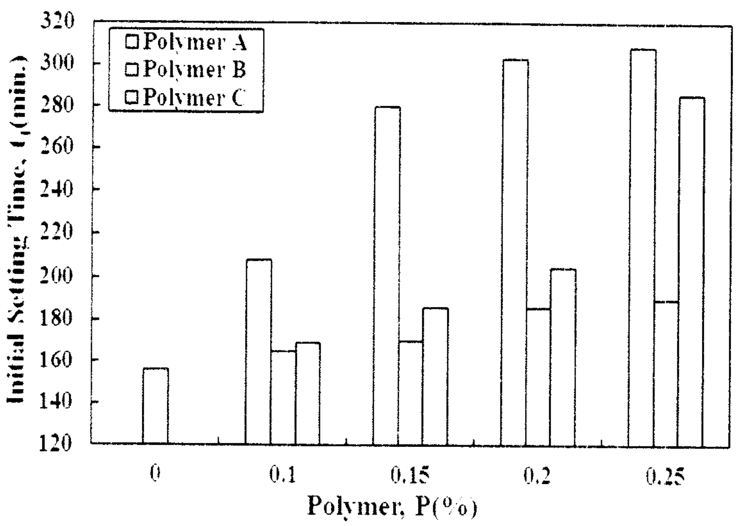


Fig. 4 Variation of the initial setting time of cement paste and polymer

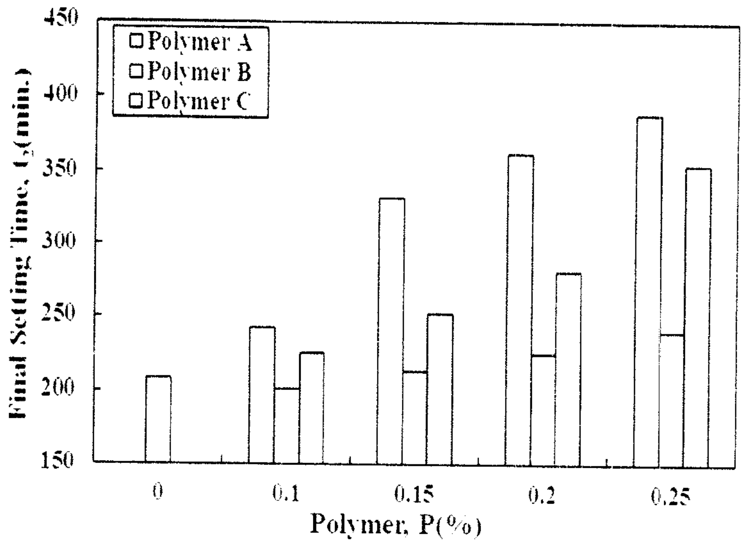


Fig. 5 Variation of the final setting time of cement paste and

3.2 Water reducing, (WR) and water to cement ratio, (w/c)

Based on the flow table test results adding polymers to the cement mortar reduced the water required to reach the standard flow as recommended by ASTM C109 (Fig.2). The correlation between the polymer contents and water reduced predicted using the Vipulanandan correlation model (Eq.1) as shown in (Fig.6). The model parameters, coefficient of determination (R^2) and root mean square error (RMSE) are summarized in Table 5. Addition of 0.25 % of polymer reduced the water content of the cement paste by 26% and 27% at the different percentage of the polymers. The w/c of the control sample was selected to be 0.5%. The correlation between polymers content and w/c were predicted using the Vipulanandan correlation model as shown in (Fig.7). The model parameters, R^2 and RMSE are summarized in Table 5.

3.3 Density

Additional of 0.25 % of polymer A, B and C increased the density of cement mortar from 2.26 g/m3 to 2.4, 2.39 g/m3 and 2.41 g/cm3 at 1day of curing as shown in (Fig.8). At 28 days of curing, the addition of 0.25 % of polymer increased the density of cement mortar by 8% to 13% based on the type of polymer and w/c as shown in (Fig.8).

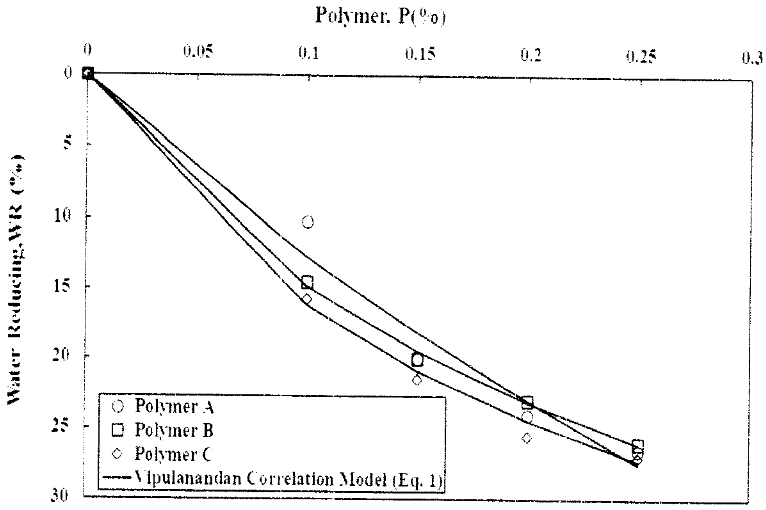


Fig. 6
Relationship between the water reducing of cement

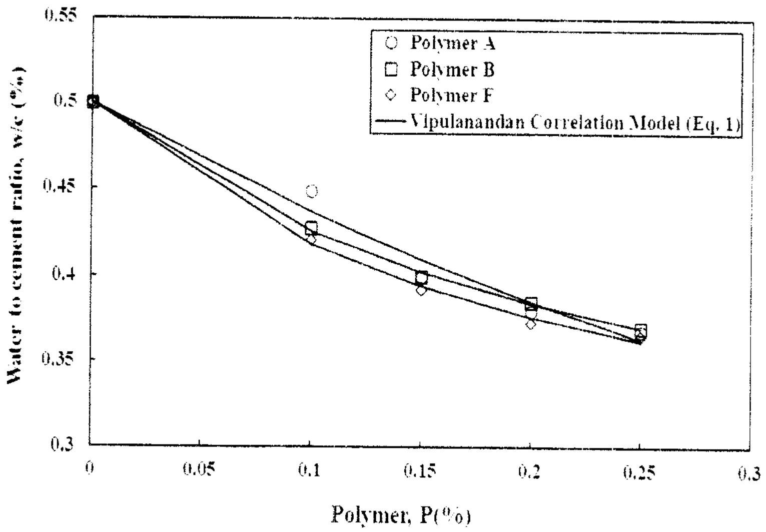
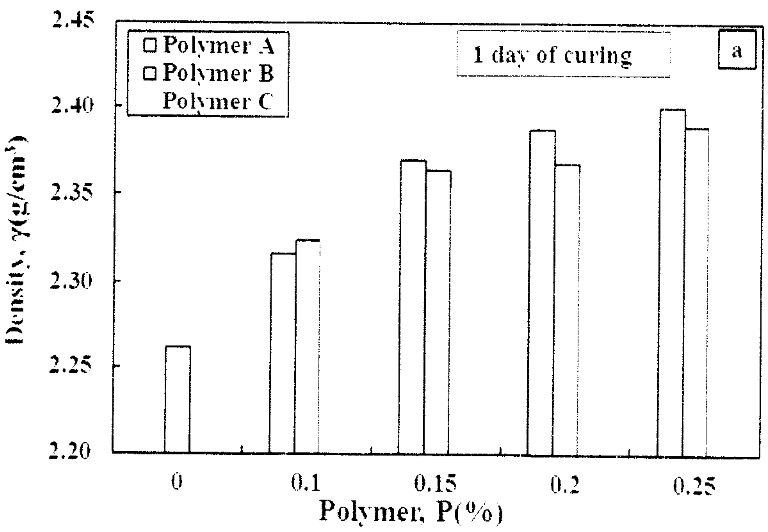


Fig. 7
Relationship between the water cement ratio of cement



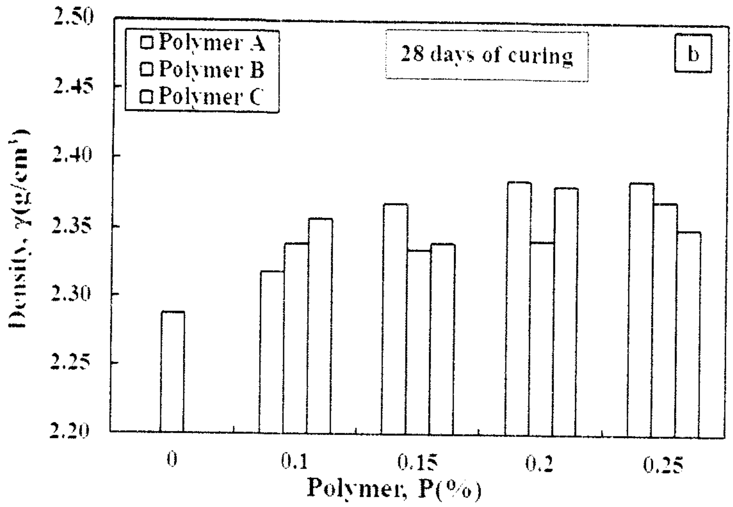


Fig. 8 Variation of the density of cement mortar modified with different types of polymer at (a) 1 day and (b) 28 days of curing mortar and polymer content mortar and polymer content polymer content content

Table 5. Model parameters for effect of different types of polymer on the consistency, water content and water to cement ratio of cement and cement mortar

In depended Variable (X axis), polymer	Depended Variable (Y axis)	Vipulanandan correlation model (Eq.1)					
		Yo	I	H	RMSE (%)	R^2	Fig.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	

3.4 Flexural strength

Adding 0.25 % of polymer A, B and C (by dry weight of cement) increased the σ_f of cement mortar from 3.5 MPa to 4.6 MPa, 4.8 MPa, and 5.2 MPa, respectively for 1day of curing as shown in (Fig.9). At 28 days of curing, the addition of 0.25 % of polymer A, B and C increased the σ_f of cement mortar by 23%, 21%, and 27% respectively as shown in (Fig.9).

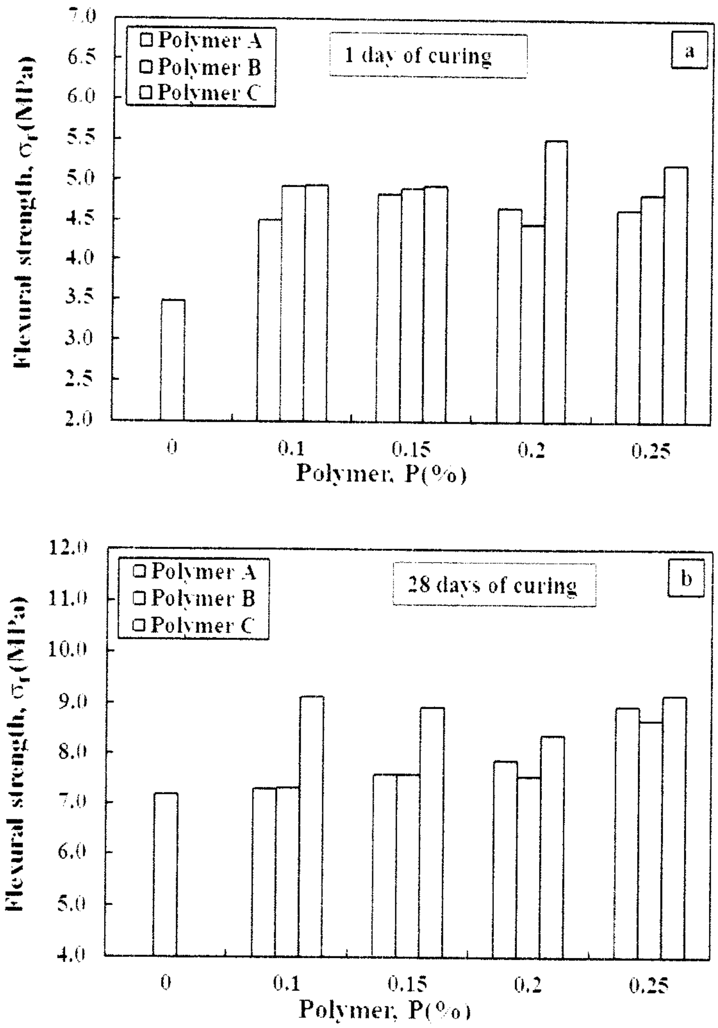


Fig.9 Variation of the flexural strength of cement mortar modified with different types of polymer at (a) 1 day and (b) 28 days of curing

3.5 Tensile bonding strength

The additional polymers improved the bond strength (σ_b) of cement mortar for 3 and 7 days of curing. At 3 days of curing, the addition of 0.25 % of polymer A, B and C increased the σ_b of cement mortar from 0.35 MPa to 0.72 MPa, 0.51 MPa, and 0.61 MPa respectively (Fig.10). At 7 days of curing the additional of 0.25 % of polymer A, B and C improved the σ_b of cement mortar by 168%, 64%, and 102% respectively as shown in (Fig.10). The types of failure between the mortar and concrete bricks were type 2 and type 4 failure based on CIGMAT CT-3 standard [27,29] as shown in (Fig.11).

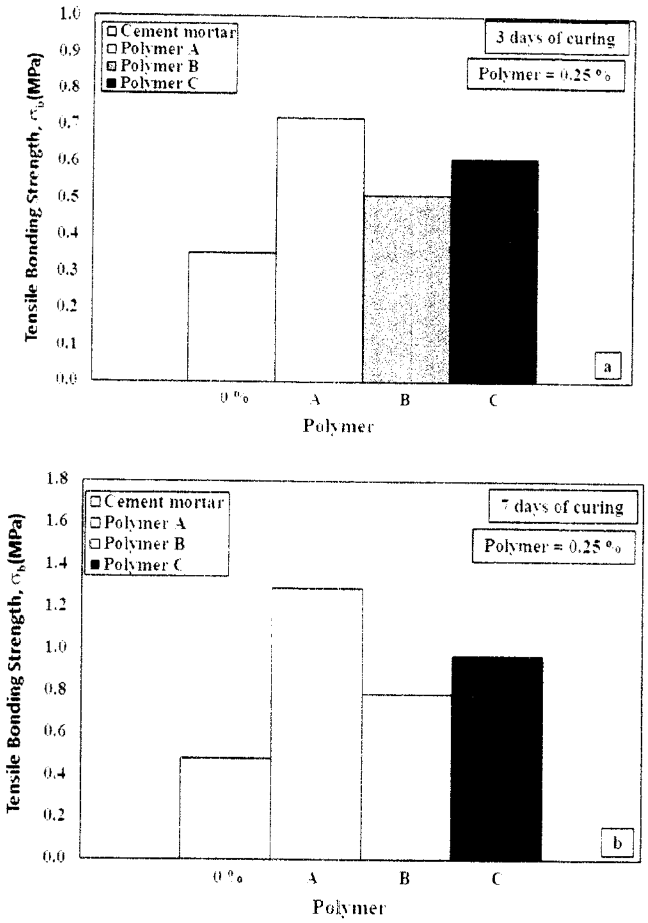


Fig. 10 Variation of the tensile bonding strength of cement mortar modified with 0.25% of polymers at (a) 3 days, and (b) 7 days of curing

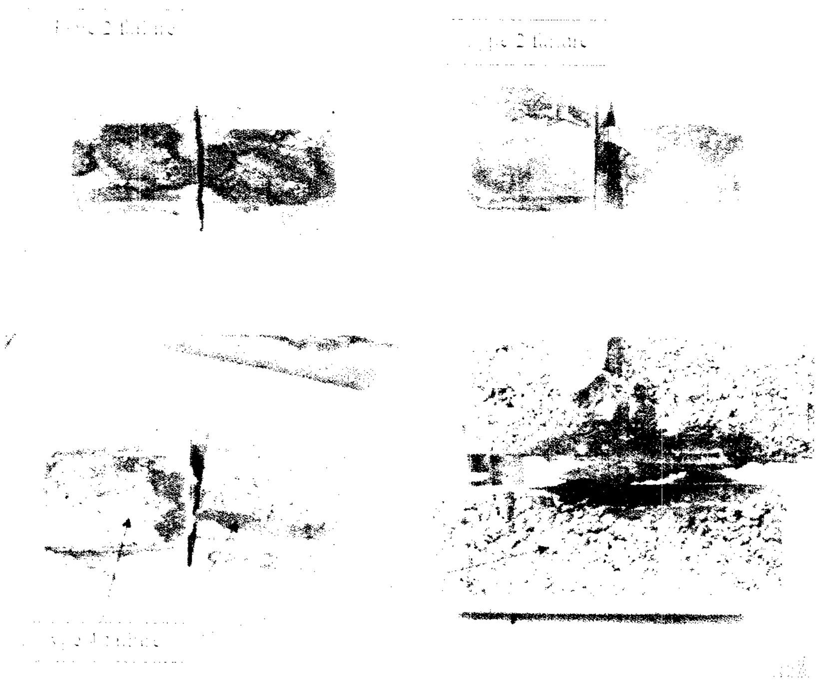


Fig. 11 Typical bonding failure for cement mortar modified with 0.25% of polymers

4. Property correlation

4.1 The relationship between polymer content and the compressive strength of cement mortar

The additional polymers were highly affected on increasing the compressive strength (σ_c) of cement mortar for up to 28 days of curing. With the increase in the percentage of polymer (P %) the compressive strength of cement mortar is nonlinearly increased as shown in (Fig.12). The variation of σ_c and P was represented using Vipulanandan correlation model (Eq.1). The model parameter, R^2, and RMSE are summarized in Table 6. At 1 day of curing additional of 0.25 % of polymer A, B and C improved the compressive strength of cement mortar by 94%, 97%, and 130% respectively. Additional of 0.25 % of polymer improved the σ_c of cement mortar by 68%, and 130% based on the type of polymer, w/c and curing time.

Table 6. Model parameters for effect of different types of polymer on the compressive strength of cement mortar

In depended Variable (X axis)	Depended Variable (Y axis)	Vipulanandan correlation model (Eq.1)					
		Yo	I	H	RMSE (MPa)	R^2	Fig.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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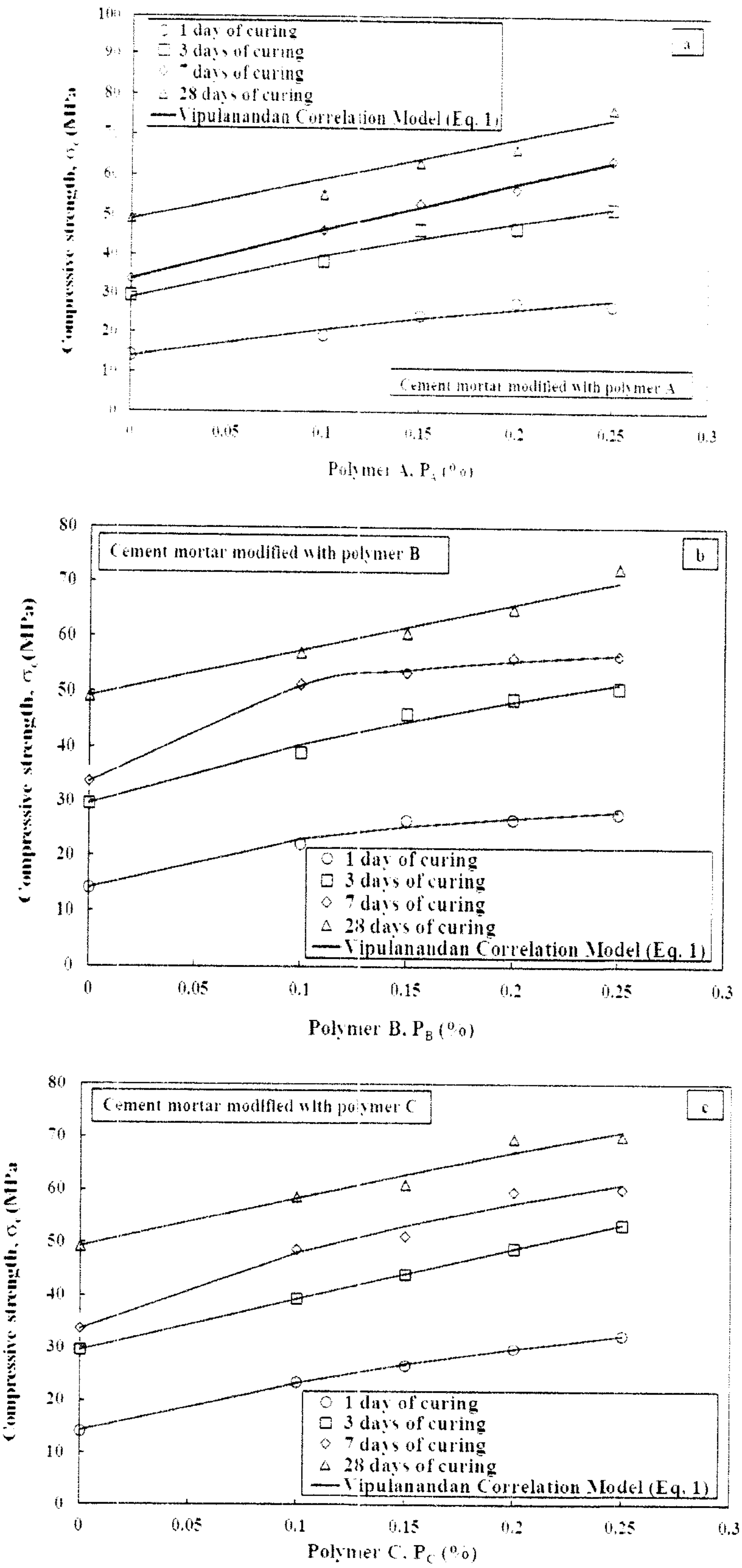

Fig. 12 Modeling the relationship between compressive strength of cement mortar and polymer content (a) Polymer A (b) Polymer B and (c) Polymer C

4.2 The relationship between measured and predicted compressive strength of cement mortar

Regression analysis was used to investigate the effect of polymers content, w/c and curing on the compressive strength of cement mortar, the compressive strength (σ_c) was correlated to the independent variables such as w/c, curing time and polymers content using a non-linear relationship (Eq.2) as shown in (Fig.13). The model parameters were obtained from multiple regression analyses using the least square method (Table 7).

(i) Polymer A (P_A)

In order to investigate the effect of polymer A on the compressive strength of cement mortar a non-linear model (Eq. 3) was developed:

$$\sigma_c = 16.85 * \left(\frac{t^{0.21}}{w/c^{0.23}}\right) + 45 * \left(\frac{t^{0.17} P_A^{\ 0.89}}{w/c^{0.29}}\right) \quad \text{No. of data} = 119,\ R^2 = 0.85 \quad (3)$$

According to the nonlinear model parameter a=16.85 (Eq. (3)) the w/c had the highest effect on increasing the compressive strength of cement mortar at 0% of the polymer as compared to the curing time. Based on the nonlinear model parameter d=45 (Eq. (3)) the polymer A had the highest effect on increasing the compressive strength of cement mortar as compared to the w/c and curing time.

(ii) Polymer B (P_B)

Non-linear model (Eq. 4) was obtained to investigate the effect of polymer B on the compressive strength of cement mortar.

$$\sigma_c = 16.85 * \left(\frac{t^{0.21}}{w/c^{0.23}}\right) + 44 * \left(\frac{t^{0.09} P_B^{\ 0.55}}{w/c^{0.16}}\right) \quad \text{No. of data} = 119,\ R^2 = 0.86 \quad (4)$$

Based on the nonlinear model parameter d=44 (Eq. (4)) the polymer B also had the highest effect on increasing the compressive strength of cement mortar as compared to the w/c and curing time.

(iii) Polymer C (P_C)

A multiple non-linear model (Eq. 5) was found to evaluate the effect of polymer C on the compressive strength of cement mortar.

$$\sigma_c = 16.85 * \left(\frac{t^{0.21}}{w/c^{0.23}}\right) + 51 * \left(\frac{t^{0.09} P_C^{\ 0.64}}{w/c^{0.19}}\right) \quad \text{No. of data} = 119,\ R^2 = 0.87 \quad (5)$$

According to the nonlinear model parameter d=51 (Eq. (5)) similar to polymer A and B, the polymer C also had the highest effect on increasing the compressive strength of cement mortar as compared to the w/c and curing time. Based on the nonlinear model parameter d= 45, 44 and 51 (Eq. (3, 4 and 5)) the polymer C had the highest effect on increasing the compressive strength as compared to polymer A and polymer B.

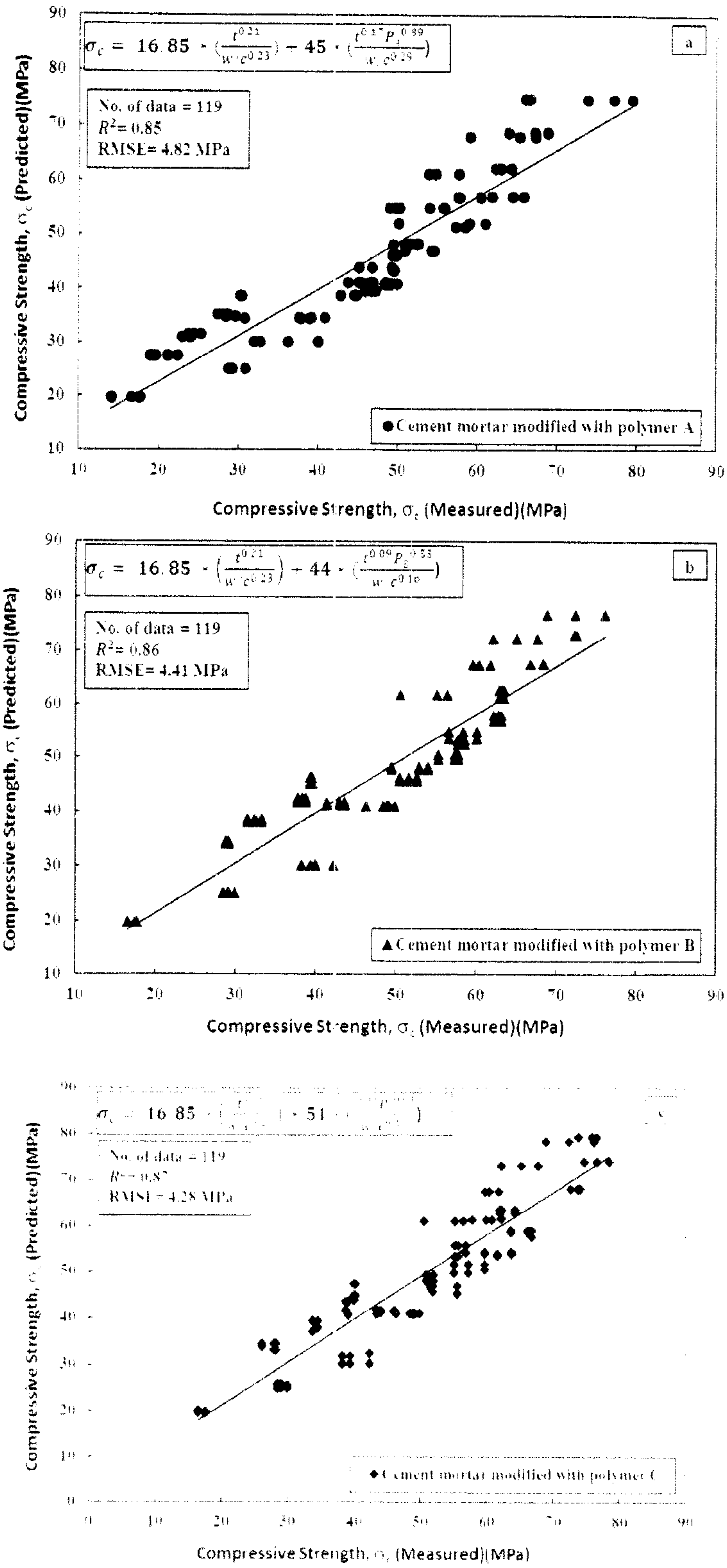

Fig. 13 Comparison between measured and predicted compressive strength of cement mortar modified with different types of polymer (a) Polymer A (b) Polymer B and (c) Polymer C

4.3 The Relationship between compressive strength (σ_c) and flexural strength (σ_f)

Based on the total of 60 experimental data for cement mortar modified with powder polymers. The variation of σ_f and σ_c was represented using the Vipulanandan correlation model (Eq.1) as shown in Fig.14. The flexural strength of cement mortar increased from 4.3 to 9 MPa when the compressive strength increased from 20 to 70 MPa for cement mortar.

$$\sigma_f = \frac{\sigma_c}{(1.41+0.06*\sigma_{c_f})} - 2.84 \qquad \text{No. of data} = 60,\ R^2 = 0.83 \qquad (6)$$

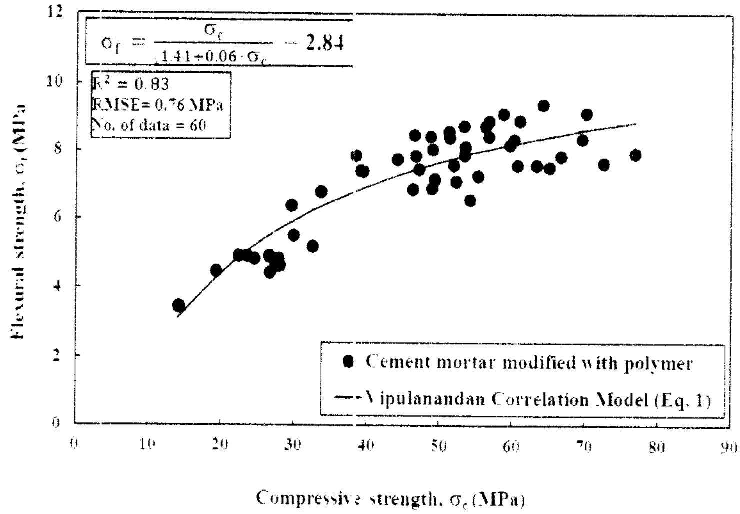

Fig. 14 Relationship between compressive and flexural strengths of cement mortar modified with polymers

Table 7. Non-linear model (NLM) parameters for the compressive strength of cement mortar modified with different types of polymer

		Cement mortar only			Effect of polymers								
Model parameters		**a**	**b**	**c**	**d**	**e**	**f**	**g**	**RMSE (MPa)**	**R^2**	**No. of data**	**Eq. No.**	**Fig. No**
Compressive strength, σ_c (MPa)	A	16.85	-0.23	0.21	45	-0.29	0.17	0.89	4.82	0.85	119	4(a)	14(a)
	B				44	-0.16	0.09	0.55	4.41	0.86	119	4(b)	14(b)
	C				51	-0.19	0.09	0.64	4.28	0.87	119	4(c)	14(c)

5. Conclusions

The focus of this study was to investigate the effect of three types of polymer on the flowability and strengths properties of cement mortar.

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