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Scientific paper

Experimental Investigation on Mechanical Properties of SBR-Modified Mortar with Fly Ash for Patch Repair Material

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Abstract

This work determines the replacement ratio of fly ash of 25% in SBR-modified cement mortars based on the past research, including SBR emulsion (SBR-E) and SBR powder (SBR-P). In addition to the Japanese guidelines for the repair material, the past researches related to polymer-modified cement mortars are also used to determine an appropriate mix proportion of the patch repair material for deteriorated RC building structures. According to the experimental results in this work, it can be observed that increasing the S/W ratio of SBR is useful to improve the flexural bonding strength effectively; however, the compressive, flexural and tensile strength of cement mortars decreases. Besides of the mechanical strength, the workability and economy are considered to determine the S/W ratio of 10% of SBR-P for cement mortars with fly ash. Additionally, according to the regression results, its corresponding compressive, flexural, tensile and flexural bonding strengths are 36.5, 9.68, 3.35 and 2.8 MPa, respectively. For most of RC buildings with an age of over 30 years in Taiwan, since their average testing compressive strength is around 20 MPa, the suggested mix proportion of SBR-modified cement mortars with fly ash can provide enough performances for the patch repair.

1. Introduction

Reinforced concrete (RC) is the most popular construction material for structures. During the 1970s in Taiwan, to improve infrastructure and industrial upgrading by national infrastructure projects. At that time, a large of bridges and RC buildings were built to upgrade the industry and the development. From the 1970s to the present, over years of wind, rain, and even frequent earthquakes, many RC buildings or structures have deteriorated even to the point of becoming dangerous. Therefore, maintaining deteriorated / damaged RC buildings or structures are a very important issue. However, in some cases, the repaired members or components cannot be protected from the re-deterioration effectively by repair material, especially in the tension sides of slabs, mainly because of the poor bonding performance between the existing concrete and the cement mortar of the repair material. Therefore, in the past several years, the polymer-modified cement mortar has been proposed as a replacement to cement mortar as a repair material.

The incorporation of synthetic polymers into Portland

cement mortar and concrete began in the 1950s (Wagner 1965). Since then, synthetic polymer latexes, such as styrene-butadiene rubber (SBR) latex in a Portland cement system, has become accepted for many applications (Hwang *et al.* 2008). Therefore, various synthetic polymer latexes are extensively used in the construction industry (Stampino *et al.* 2009). However, commercial polymer-modified cement mortar products for repair are much more expensive than ordinary cement mortars. Moreover, since most commercial per-modified cement mortar products are made as premix cement powder, their components cannot be adjusted to meet particular requirements. For example, according to the past investigation in Taiwan, many typical RC buildings with an age of greater than 30 years have been seriously degraded by carbonation or chloride ions. Additionally, their compressive strength of concrete, obtained by drilled-cores testing methods, does not exceed 20 MPa (Zheng *et al.* 2015). Therefore, how to select an appropriate mixing proportion of polymer-modified cement mortars for these RC buildings becomes an important issue in Taiwan. To reduce the cost of the repair material, the goal of this work is to replace some of the cement in polymer-modified cement mortars with fly ash. Furthermore, this work would like to conduct the experiment to investigate the effect of synthetic polymer latexes on the mechanical properties of cement mortars with fly ash.

Fly ash is used as a supplementary cementitious material (SCM) in the production of Portland cement concrete (Thomas 2007), which has many advantages to enhance concrete performances, such as flowability of fresh concrete, the late strength of concrete, resistance against ASR or ingress of corrosive factors (Bilir *et al.* 2015; Fanghui *et al.* 2015). However, a shortage of fly

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Table 1 Limits on cementitious materials for concrete assigned.

Cementitious materials	Maximum percent of total cementitious materials by mass
Fly ash or other Pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or other Pozzolans and silica fume	35
Total of fly ash or other Pozzolans, slag cement and silica fume	50

ash is currently resulting in low early-age strength (Thomas 2007). **Table 1** shows the limits on the quantity of supplementary cementitious materials for concrete members (ACI 2014). Additionally, based on the previous research (Kao *et al.* 2015), with the curing time increasing, the results show that the mechanical properties of the mortar with the fly ash (maximum replacement ratio is 25%) are nearly close to the mortar without any fly ash. In this work, the replacement ratio of fly ash in cement mortars is determined to be 25%. Since SBR is a popular and cheap polymer admixture in Taiwan, SBR emulsion (SBR-E) and SBR powder (SBR-P) are utilized to modify the cement mortar. The compressive strength, flexural strength and flexural bonding strength of cement mortar specimens with SBR and fly ash are studied to determine the mechanical properties of SBR-modified cement mortars with fly ash. In this work, the water/binder ratio (W/B) and latex solid/water ratio (S/W) are the mixing ratios of the SBR-modified cement mortars with fly ash. The S/W ratio is defined as the ratio of weight of solid latex to total weight of water in cement composite, including the water in the latex on the basis of the Diab's research (Diab 2013). The Japanese guidelines (AIJ 1997) for the repair material and various studies of polymer-modified cement mortars are used to determine appropriate mixing ratios of SBR-modified cement mortars with fly ash as the patch repair material that can be used in deteriorated RC building structures.

2. Literature review

2.1 Method of the patch repair

Patch repair is usually applied to repair unfilled regions or low-quality regions of RC structures and concrete that is suffering from cracking and peeling or exhibits corrosion-induced deterioration. It is also used to remove substances that diffuse into concrete and cause deterioration of concrete, such as chloride ions (Makishima *et al.* 2010; JSCE 1997). When a concrete region has undergone corrosion-induced deterioration in an RC member, the patch repair method usually involves removing all of the substrate concrete with a high chloride content and then applying rust a treatment to the steel bars (Makishima *et al.* 2010; Ohama 1996). A suitable finishing material should be used to cover the repaired area to renew its surface and seal the defective region, as shown in Fig. 1.

The Japanese guidelines for concrete repair and the surface protection of concrete structures (AIJ 1997) recommend three practical methods of patch repair for use in various deteriorated regions of RC members; i.e., plastering method, spraying method, and filling processing method. Appropriate materials must be chosen according to the specified performance, standards and construction method.

2.2 Required performance of patch repair materials

The materials that are used in patch repair must have better mechanical properties than concrete, e.g., compressive strength, flexural strength and tensile strength, and high compatibility with the substrate concrete (AIJ 1997). Additionally, repair materials can have the appropriate ability to form effective barriers against the penetration of the deterioration factors (e.g., chloride ions, carbon dioxide or freeze-thaw cycles) by improving the mechanical properties. However, physical properties must also be considered in selecting materials for repair work. Although a high cement content in repair material can increase its compressive strength, the strength may be reduced by cracking or dry shrinkage (CHES 2005; Li 2000; Cusson and Mailvaganam 1996; Morgan 1996).

Elastic modulus is an important measure of rigidity. When two materials with different elastic modulus materials are constructed in one region or member, e.g.,

Fig. 1 Patch repair method.

repair material and existing concrete, a higher modulus material imposes a great constraint on the transverse contraction of the lower modulus material. To avoid such a situation, the repair material should have a similar elastic modulus to that of the substrate concrete (Li 2000). Dry shrinkage is a property of cement paste. The substrate concrete restrains the shrinkage of the repair material, inducing stress on the repair material. This stress promotes cracking easily. During cracking, the structure deteriorates further. Therefore, a repair material should have a low or zero dry shrinkage rate. Materials with a high early-age strength are used to satisfy construction requirements. However, such materials exhibit high early-age strength, dry shrinkage and thermal expansion. Therefore, for satisfying the construction requirements, high early-age strength products should not be used as repair materials (Li 2000; Cusson and Mailvaganam 1996; Morgan 1996; Abbasnia *et al.* 2005). If the repair material does not bond with sufficient strength with the substrate-concrete, then it will not exhibit its original properties. Treatment of the substrate-concrete interface also importantly affects the substrate concrete; it can remove deteriorated concrete and cleaning the dust on the substrate concrete interface and so on. (Li 2000; Morgan 1996).

2.3 Polymer-modified cement mortars

The three repair materials that are used in construction are polymer-modified cement mortars, epoxy mortars and cement mortars. The cement mortar is the most compatible with substrate concrete because it has similar strength, a similar modulus of elasticity, a similar thermal modulus and other similar properties to those of substrate concrete. It is also easy to mix and use in construction. It is useful for repairing large areas. Its disadvantages include its low electrical resistance, which is difficult to resist the degradation factor of concrete.

The advantages of polymer-modified cement mortars are its strong bonding with substrate concrete and its low shrinkage rate, which disfavors cracking. It also exhibits high flexural strength, tensile strength and resistance to deterioration. It is also easy to mix and use in construction. Some experiments show that the cement-based materials form stronger bonding with substrate concrete than the resin materials while polymer-modified cements have higher bond strength. However, some polymer-modified cement mortars and epoxy mortars perform inadequately in hydraulic structures subjected to severe sites or climatic conditions because they are not thermally compatible with the base concrete and their bonding to wet concrete surfaces is poor.

Mirza (2002) found that most polymer-modified cement-based mortars have greater resistance to compression and abrasion, and lower permeability, than reference cement mortar and they form stronger bonds. Polymer-modified cement mortars usually exhibited the best compressive and bond strengths, and resistance to

abrasion and shrinkage under wet curing conditions. Dry curing led to greater shrinkage. Ohama's elucidated the following general requirements for polymer latexes as polymer-based admixtures (Ohama 1998).

- 1) Highly chemically inert towards extremely active cations.
- 2) Very high mechanical stability under severe conditions-especially high shear in mortar.
- 3) Low air-entraining action when suitable antifoaming agents are used during mortar mixing.
- 4) No adverse effect on cement hydration.
- 5) Excellent water resistance, alkali resistance and weather-ability of the polymer films that form in mortar.
- 6) Thermal stability over wide range of temperatures during transportation and storage.

Diab (2013) focused on a newly identified factor that significantly affects the properties of latex-modified mortar or concrete. This factor is defined as the ratio of the weight of solid latex to the weight of total water in the mortar. The results of Diab's experiments on cement paste indicated that the degree of cement hydration considerably decreases as the SBR solid/water ratio increases to a limit of 0.2. Moreover, increasing the latex concentration tremendously very strongly affects the modified co-matrix structure and its mechanical properties. X-ray diffraction tests indicated that the developed ettringite content increased with the solid latex content. A higher ettringite content is associated with wet curing increases ettringite formation. The developed calcium hydroxide content exhibited a different trend. Based on experimental evidence, calcium hydroxide content decreases as the SBR solid/water ratio increases. Diab also indicated that the compressive strength of modified concrete improves as the SBR solid/water cement ratio increases to a limit of 0.20. Moreover, the flexural strength of latex-modified concrete increases with the SBR solid/water ratio increases. The ductility of the latex cement co-matrix increases with the latex concentration increases, while the modulus of elasticity of the co-matrix decreases as the latex solid/water ratio increases. The drying shrinkage strain of the latex-modified co-matrix decreases as the latex concentration increases.

Since polymer-based admixtures affect the physical and mechanical properties of cement mortars, as well as its durability, this investigation collects test data from previous investigations of various polymer materials, e.g., SRB, PAV, EVA, and VVA (Hamasaki *et al.* 2010; Takahashi *et al.* 2013). Since most polymer materials are commercial products that are mixed with cement to form repair materials, the detailed compositions of commercial products cannot be made public. **Figure 2** shows the mechanical properties of cement mortars that are modified using various polymer admixtures but only the main components are specified. According to **Fig. 2**, the compressive strength of cement mortars without any polymer materials is obviously higher than poly-

mer-modified cement mortars. However, the experimental results of the compressive strength are not consistent with the conclusion proposed by Diab (2013). Additionally, few researches related to polymer-modified cement mortars with fly ash can be referred. Therefore, for the practical use for the existing RC structures with the compressive strength ≤ 20 MPa, it is necessary to investigate the mechanical properties of SBR-modified cement mortars with fly ash using the experiment.

3. Experiment

3.1 Materials

The experimental materials that are used in this work include cement (density: 3.15 g/cm^3), sand (density: 2.61 g/cm^3) and fly ash. The selected fly ash is F-type that is specified in American Society for Testing and Materials (ASTM) and its properties are presented in Table 2.

SBR emulsion (SBR-E) and SBR powder (SBR-P) (Figs. 3 and 4) are used herein. Table 3 presents the physical and chemical properties of SBR-E, provided by the manufacturer in Taiwan, and Table 4 presents the results of an analysis of SBR-P. These two polymer materials can be dissolved in water and are easy to be

used in the practical work.

3.2 Mix proportion

The mixing ratio of the cement to sand in cement mortars that is used in this investigation is 1:3. Table 5 shows the various mixes in this work. The latex solid/water ratio (S/W) is used to set the dosage of SBR-E or SBR-P. Based on Diab's research (Diab 2013), the S/W ratio herein is defined as the ratio of the weight of solid latex to the total weight of water in the cement composite, including the water in the latex. As well as the S/W ratio, Table 5 presents the P/C ratio, which is defined as the ratio of the weight of solid latex to the weight of cement. All specimens are water-cured for the first seven days and air-cured for the following eight days. This work uses some mechanical testing methods specified in ASTM to investigate the compressive, tensile, flexural and flexural bonding strengths.

3.3 Testing method

Experimental data is collected to determine whether meets the specifications for patch repair material that are set by the Architectural Institute of Japan (AIJ 1997). According to AIJ (1997), Table 6 presents the required compressive, tensile and pull-out bonding strengths for

Fig. 2 Mechanical properties of the polymer-modified cement mortar in Japan.

Table 2 Properties of fly ash.

Density (g/cm ³)	Specific surface area (cm ² /g)	Glass content (%)	Ignition loss (%)	Chemical composition (%)						
				SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	Na ₂ O	K ₂ O	Na ₂ Oeq
2.25	2530	75.3	2.82	60.7	20.7	2.71	5.70	1.18	1.24	2.00

Table 3 Physical and chemical properties of SBR-E.

Items	Results
Form / Colour / Odour	Milky white liquid with a mild acrylic odour
Solubility:	Miscible with water
Specific Gravity (20°C):	1.02
Relative Vapour Density (air=1):	< 1
Vapour Pressure (kPa @ 20°C):	2.3
Melting Point/Range (°C):	
Boiling Point/Range (°C):	Approx. 100
pH:	9.8 – 10.8
Viscosity (cS):	< 500

Table 4 Analytic report of SBR-P.

Items	Unit	Results
BD/SM ratio	%	67/33
Oil content	Phr	0
Viscosity	cps, 25°C	14
Particle density	g/cm ³	0.782
Ash	wt%	< 0.2
Volatile material	wt%	< 0.4

patch repair material. In this work, the flexural bonding test, rather than the pull-out bonding test, is used to quantify the bonding performance of the patch repair material.

The tests in this work adopt the following standard testing methods.

- 1) ASTM C1437 Standard test method for flow of hydraulic cement mortar
- 2) ASTM C109 Standard test method for compressive strength of hydraulic cement mortars
- 3) ASTM C190 Method of test for tensile strength of

hydraulic cement mortars

- 4) ASTM C348 Standard test method for flexural strength of hydraulic-cement mortars

Figure 5 shows the specimens that are used herein to test the flexural bonding strength. At first, the substrate mortar of a specimen is poured by cement mortars with the W/B ratio of 0.5. Then, the substrate mortar is cured in water for seven days and in the air for 14 days. A specified surface, which is in contact with the repair material, is made rough and painted with wax with a depth of approximately 1 cm. Since the cross-sectional area of the specified surface between the substrate mortar and repair material is smaller than the other sectional area in the specimens, they would break at the specified surface under the applied loading. Finally, according to ASTM C348 for the flexural strength of hydraulic cement mortars, the testing flexural bonding strength can be calculated using the flexural formula.

3.4 Results

In this work, flow, compressive strength, tensile strength, flexural strength and flexural bonding strength are tested. Although the mixture proportions and curing conditions are almost the same, the different construction time of specimens scatter the experimental results. However, the trends of the experimental results still can be used to do the investigation on the mechanical properties of cement mortars. At first, the flow, compressive strength and flexural strength, which are the most basic required performance in practice, are investigated herein to comprehend the effect of SBR and fly ash on the mechanical properties of cement mortars.

Fig. 3 SBR-E.

Fig. 4 SBR-P.

Table 5 Mixture proportions.

Notation	Fly ash replacement ratio	W/B	S/W	P/C	Amount of material (kg/m ³)					Unit price (^{TWD} /m ³)
					Sand	Cement	Fly ash	Water	SBR	
F00SL00-50*	0%	50%	0%	0.00%	1525.2	508.4	-	254.2	-	2456
F00SL05-50			5%	2.42%	1518.9	506.3	-	245.0	20.4	5098
F00SL09-50			9%	4.24%	1514.4	504.8	-	238.1	35.7	7080
F00SL10-50			10%	4.69%	1513.2	504.4	-	236.4	39.4	7559
F00SL12-50			12%	5.56%	1511.1	503.7	-	233.2	46.7	8505
F00SL14-50			14%	6.41%	1509.0	503.0	-	230.0	53.7	9411
F00SL15-50			15%	6.82%	1507.8	502.6	-	228.5	57.1	9851
F00SL18-50			18%	8.04%	1504.8	501.6	-	223.9	67.2	11159
F00SL20-50			20%	8.83%	1502.7	500.9	-	221.0	73.7	12001
F25SL00-50	25%	50%	0%	0.00%	1500.9	375.2	125.1	250.2	-	1917
F25SL05-50			5%	3.23%	1494.9	373.7	124.6	241.1	20.1	4522
F25SL09-50			9%	5.67%	1490.4	372.6	124.2	234.3	35.2	6479
F25SL10-50			10%	6.25%	1489.5	372.4	124.1	232.7	38.8	6946
F25SL12-50			12%	7.41%	1487.1	371.8	123.9	229.5	45.9	7866
F25SL14-50			14%	8.55%	1485.0	371.3	123.8	226.3	52.9	8774
F25SL15-50			15%	9.09%	1484.1	371.0	123.7	224.9	56.2	9201
F25SL18-50			18%	10.73%	1481.1	370.3	123.4	220.4	66.2	10498
F25SL20-50			20%	11.76%	1479.3	369.8	123.3	217.6	72.5	11314
F00SL00-45	0%	45%	0%	0.00%	1565.1	521.7	-	234.8	-	2521
F00SL12-45			12%	5.00%	1551.6	517.2	-	215.5	43.1	8102
F00SL15-45			15%	6.14%	1548.6	516.2	-	211.2	52.8	9358
F25SL00-45	25%	45%	0%	0.00%	1539.6	384.9	128.3	230.9	-	1966
F25SL12-45			12%	6.67%	1526.4	381.6	127.2	212.0	42.4	7461
F25SL15-45			15%	8.19%	1523.4	380.9	127.0	207.7	52.0	8706
F00SP00-50	0%	50%	0%	0.00%	1525.2	508.4	-	254.2	-	2456
F00SP05-50			5%	2.50%	1500.9	500.3	-	250.2	12.5	3598
F00SP10-50			10%	5.02%	1477.2	492.4	-	246.2	24.7	4713
F00SP15-50			15%	7.51%	1454.4	484.8	-	242.4	36.4	5782
F00SP20-50			20%	10.01%	1431.9	477.3	-	238.7	47.8	6823
F25SP00-50	25%	50%	0%	0.00%	1500.9	375.2	125.1	250.2	-	1917
F25SP05-50			5%	3.33%	1477.5	369.4	123.1	246.3	12.3	3049
F25SP10-50			10%	6.68%	1454.4	363.6	121.2	242.4	24.3	4154
F25SP15-50			15%	10.00%	1432.2	358.1	119.4	238.7	35.8	5212
F25SP20-50			20%	13.36%	1410.6	352.7	117.6	235.1	47.1	6252

* F00SL00-50* is "F00" is presented as fly ash replacement ratio 0%, "SL00" shows that S/W ratio of 0 and SBR-E, SBR-P shows as "SP", and "50" is presented to W/B ratio of 0.5.

Table 6 Guideline of the patch repair material. (AIJ 1997)

Test	Compressive strength	Flexural strength	Bonding strength
Required value	20 MPa	6.2 MPa	1 MPa

Fig. 5 Specimens of flexural bonding strength tests.

(1) Flow

Figure 6(a) shows that as the S/W ratio of SBR-E increases at the W/B ratio of 0.45, the flow values of the specimens without any fly ash increase from 100 mm to 220 mm. Additionally, the flow values of the specimens with fly ash increase from 110 mm to 177 mm. For the specimens with SBR-E and the W/B ratio of 0.50 in **Fig. 6(b)**, flow values follow the same trend as the W/B ratio of 0.45. From **Figs. 6(a)** and **6(b)**, fly ash cannot increase the flow of the specimens with SBR-E. For the specimens with SBR-P and a W/B ratio of 0.50, **Fig. 6(c)** shows SBR-P clearly reduces the flow values,

mainly because SBR-P must be dissolved in water during the mixing procedure. As an example, the S/W ratio of 10% in the specimens with fly ash and SBR-P yields the flow value of approximately 125 mm, which is less than that (around 140 mm) at a S/W ratio of 0.0%.

(2) Compressive strength

Figure 7 shows that the compressive strength of the specimens decreases as the S/W ratio increases and that fly ash reduces the compressive strength of the specimens. Generally, the compressive strength of the specimens with the W/B ratio of 0.45 exceeds that of the

Fig. 6 Flow values of the specimens.

specimens with the W/B ratio of 0.50. However, when the S/W ratio is 15%, the compressive strength of the specimens with the W/B ratio of 0.50 and SBR-P is not less than that of the specimens with the W/B ratio of 0.45 and SBR-E. Moreover, the decrease of the compressive strength of the specimens with the W/B ratio of 0.50 and SBR-E becomes smaller as the S/W ratio increases above 10% (Fig. 7(b)). According to Figs. 7(b)

(a) SBR-E and W/B ratio of 0.45.

(b) SBR-E and W/B ratio of 0.50

(c) SBR-P and W/B ratio of 0.50

Fig. 7 Compressive strength of the specimens.

and 7(c), the decrease of the compressive strength of the specimens with SBR-E is more serious than SBR-P. Restated, SBR-E reduces the compressive strength of specimens more than SBR-P. Moreover, although fly ash and SBR reduce the compressive strength of specimens, the compressive strength of each specimen that is cured for 28 days still meets the requirement of 20 MPa.

(3) Flexural strength

Figure 8 shows that the flexural strength of the specimens decreases as the S/W ratio increases and that fly ash also reduces the flexural strength of the specimens. The flexural strength of the specimens with the W/B ratio of 0.45 exceeds that of specimens with the W/B ratio of 0.50; however, when the S/W ratio exceeds 12%, the flexural strength of the specimens with the W/B ratio of 0.50 and SBR-P is not less than that of the specimens with the W/B ratio of 0.45 and SBR-E. For the specimens with the W/B ratio of 0.50 and SBR-E (Fig. 8(b)), fly ash has little effect on flexural strength; however, it still causes some of the obtained values of flexural strength below the required value of 6.0 MPa. Obviously, the variation of the flexural strength of the specimens with SBR-E is larger than that of the specimens with SBR-P. According to Figs. 8(b) and 8(c), SBR-E reduces the flexural strength of the specimens more than SBR-P, which is similar to the compressive strength. Although fly ash and SBR reduce the flexural strength of the specimens, the flexural strength of most of the specimens that are cured for 28 days exceeds with the requirement of 6.0 MPa.

4. Investigation on the S/W ratio of SBR-E for the cement mortar with fly ash

According to the experimental results in the preceding section, the compressive strength and flexural strength of the specimens that contain SBR-E and fly ash (replacement ratio of 25%) satisfy with the AIJ specifications for the patch repair material. Therefore, this section explores the tensile strength and flexural bonding strength further, which are also important mechanical properties of the patch repair material. Based on the investigation results, an appropriate S/W ratio of SBR for modifying cement mortars with fly ash for the patch repair material is suggested.

4.1 Tensile strength

Figure 9 shows the tensile strength of the specimens. This value is not a performance metric for the patch repair material that is specified by the AIJ (1997). The tensile strength of the specimens with SBR-E that are cured in 28 days decreases as the S/W ratio increases when the S/W ratio increases up to 10%. Obviously, fly ash also reduces the tensile strength. However, for the specimens with fly ash and SBR-E, the tensile strength at the W/B ratio of 0.50 is not lower than that at the W/B ratio of 0.45. Additionally, a comparison of the values of

flow, compressive strength, flexural strength and tensile strength that are obtained at the W/B ratios of 0.50 and 0.45 indicates that adding fly ash and SBR-E to specimens with the W/B ratio of 0.45 negligibly improves their mechanical properties, whereas the improvement of properties of the specimens with the W/B ratio of 0.50 is significant. Therefore, for economic

reasons, the W/B ratio of 0.45 is not considered in the attempt to find an appropriate S/W ratio of SBR-E or SBR-P in cement mortars with fly ash in the latter section. Based on **Fig. 9** for the specimens with fly ash and the W/B ratio of 0.5, when the S/W ratio of SBR is larger than 10%, the tensile strength of the specimens with SBR-P exceeds that of the specimens with SBR-E. Obviously, as the S/W ratio of SBR increases above 10%, the tensile strength trends to be constant instead of decreasing.

4.2 Flexural bonding strength

The AIJ (1997) sets a required pull-out bonding strength of 1.0 MPa for the patch repair material. According to relevant research, the pull-out bonding strength of cement mortars with SBR-P and fly ash (replacement ratio of 25%) meets the requirement of 1.0 MPa. Since the patch repair fails easily in the tension side of an RC member, the flexural bonding strength is more important than the pull-out bonding strength in evaluating the bonding performance of the patch repair material. Therefore, the flexural bonding strength is used herein to find an appropriate S/W ratio of SBR-P in cement mortars with fly ash.

Figure 10 shows that the flexural bonding strength of the specimens increases with the S/W ratio increasing and fly ash increases the flexural bonding strength of the specimens that are cured in 28 days. The flexural bonding strength of the specimens with SBR-E exceeds that of the specimens with SBR-P. However, when the S/W ratio is less than 15%, the difference in the flexural bonding strength between SBR-P and SBR-E specimens with fly ash is not significant. Since SBR-E decreases compressive strength and flexural strength more than SBR-P, SBR-P is favored herein as the patch repair material.

4.3 Recommended S/W ratio of SBR for the cement mortar with fly ash

To find an appropriate S/W ratio of SBR for use in

(a) SBR-E and W/B ratio of 0.45

(b) SBR-E and W/B ratio of 0.50

(c) SBR-P and W/B ratio of 0.50

Fig. 8 Flexural strength of the specimens.

Fig. 9 Tensile strength of SBR-modified cement mortars with fly ash.

cement mortars, a regression analysis of the mean testing strengths is performed, as shown in **Fig. 11**. Additionally, the regression results of cement mortars with fly ash and SBR-P (W/B: 0.5; replacement ratio of 25% for fly ash)

Fig. 10 Flexural Bonding strength of cement mortars with SBR and fly ash.

are listed as Eqs. (1) - (4). **Figure 11** shows that the compressive, flexural and tensile strengths decrease as the S/W ratio increases, and fly ash also reduces the compressive, flexural and tensile strengths of SBR-modified cement mortars. **Figure 11(a)** shows that as the S/W ratio of SBR-P increases, the compressive strength of specimens without any fly ash decreases from 52.5 MPa to 40.5 MPa. Additionally, the compressive strength of the specimens with fly ash decreases from 41.0 MPa to 33.9 MPa. The flexural strength of the specimens with SBR-P in **Fig. 11(b)** exhibits the same trend as the compressive strength. Based on **Figs. 11(a)-11(c)**, although fly ash and SBR reduce the compressive, flexural and tensile strength of all of the specimens, **Fig. 11(d)** indicates that fly ash greatly increases the flexural bonding strength of specimens with SBR-P.

All of the regression results, which are plotted in **Fig. 11** indicate a linear relationship between compressive and flexural strengths and after a curing period of 28 days, the compressive and flexural strengths meet the AIJ (1997) requirements. The appropriate S/B ratio of SBR-P

(a) Compressive strength

(b) Flexural strength

(c) Tensile strength

(d) Flexural bonding strength

Fig. 11 Regression analysis of each strength.

in cement mortars with fly ash is also to be determined considering the compressive strength or flexural strength of specified buildings for which patch repair work is planned. Since the average testing compressive strength of most of RC buildings with an age of over 30 years in Taiwan is not more than 20 MPa, the recommended mixing ratio of SBR-modified cement mortars with fly ash must provide the patch repair material with the consistent performance. Therefore, this work determines the maximum S/W ratio of SBR-P from the minimal values of compressive strength and flexural strength that are stated in **Fig. 2**, which are 34.5 and 8.2 MPa, respectively. According to the regression results in **Fig. 11**, the corresponding maximum S/W ratios of SBR-P are 14.3% and 17.9%, respectively. Additionally, if the required flexural bonding strength is set to 3.0 MPa, which is determined from the tensile strength, then the S/W ratio of SBR should be adjusted to 11.1%. However, as well as mechanical strength, workability and economy should be considered to determine an appropriate S/W ratio of SBR. Accordingly, 10.0% SBR-P is recommended for cement mortars with fly ash. According to **Fig. 11**, for cement mortars with fly ash and SBR (whose S/W ratio is 10.0%), the corresponding compressive, flexural, tensile and flexural bonding strengths are 36.5, 9.68, 3.35 and 2.8 MPa, respectively. If required, based on the regression results in this work, the S/B ratio of SBR-P can be reduced to increase compressive, flexural and tensile strengths but flexural bonding strength will then be reduced. However, the lower bound on the S/W ratio of SBR-P can be set to 6.8% based on the crossing point of the two regression lines in **Fig. 11(d)**. If the S/W ratio of SBR-P is below the crossing point, then SBR does not improve the mechanical properties of SBR-modified cement mortars with fly ash.

$$f'_c = -45.98 \left(\frac{S}{W} \right) + 41.09 \text{ (MPa)} \quad (1)$$

$$f_r = -18.78 \left(\frac{S}{W} \right) + 11.56 \text{ (MPa)} \quad (2)$$

$$f_t = -6.82 \left(\frac{S}{W} \right) + 4.03 \text{ (MPa)} \quad (3)$$

$$f_b = 13.72 \left(\frac{S}{W} \right) + 1.47 \text{ (MPa)} \quad (4)$$

where f'_c is the mean value of the compressive strength, f_r is the mean value of the flexural strength, f_t is the mean value of the tensile strength and f_b is the mean value of the flexural bonding strength.

This work also investigates the mechanical properties of SBR-modified cement mortars with fly ash at various curing periods of 7, 28 and 56 days, as shown in **Fig. 12**. All specified mechanical properties are improved as the curing time increases. The S/W ratio of SBR-P clearly

influences the rate of increase of the compressive strength with curing time. Furthermore, at some S/W ratios of SBR-P, the compressive strength remains almost constant as the curing period increases. Obviously, fly ash still has the contribution on the strength development when the curing time increases.

5. Conclusion

This work determines the replacement ratio of fly ash of 25% in SBR-modified cement mortars based on the past research, including SBR emulsion (SBR-E) and SBR powder (SBR-P). The Japanese guidelines for the repair material, the past researches related to polymer-modified cement mortars are also used to determine an appropriate mixing proportion of the patch repair material for deteriorated RC building structures. Experimental results for the S/W ratios of 0.0 - 20% support the following conclusions:

- 1) SBR-E increases the workability of cement mortars with and without fly ash; however, SBR-P greatly reduces the flow value to an extent that increases with its S/W ratio. Fly ash does not significantly improve the workability of SBR-modified cement mortars. Restated, besides of the W/B ratios in cement mortars, SBR affects the workability of cement mortars significantly.
- 2) The decrease of the compressive strength of the specimens with the W/B ratio of 0.50 and SBR-E becomes smaller when the S/W ratio exceeds 10%. SBR-E reduces the compressive strength of the specimens more than SBR-P. The difference between the compressive strengths of the SBR-P specimens with and without fly ash becomes smaller as the S/W ratio of SBR-P increases.
- 3) For the specimens with the W/B ratio of 0.50 and SBR-E, fly ash has less effect on the flexural strength than on the compressive strength. SBR-E reduces the flexural strength of the specimens more than SBR-P and this difference is similar with the development in compressive strength. Additionally, the difference between the flexural strength of the SBR-P specimens with and without fly ash is small when the S/W ratio of SBR-P is less than 10%.
- 4) According to the experimental results at the W/B ratio of 0.5, when the S/W ratio is less than 15%, the difference in the flexural bonding strength obtained using SBR-P and SBR-E is not significant and can be neglected. Since SBR-E decreases the compressive strength and flexural strength more than SBR-P, SBR-P is favored for use as the patch repair material.
- 5) SBR-P improves the flexural bonding strength of cement mortars with and without fly ash; however, the compressive strength, tensile strength and flexural strength decrease as the S/W ratio of SBR-P increases.

Fig. 12 Mechanical properties under various curing periods.

- 6) As well as the mechanical strength, workability and cost are considered in determining an appropriate S/W ratio of SBR. For most RC buildings with an age of over 30 years in Taiwan, which have the average testing compressive strength of approximately 20 MPa, 10.0% of SBR-P is recommended for cement mortars with fly ash (replacement ratio of 25%). According to the regression results, the compressive, flexural, tensile and flexural bonding strengths are 36.5, 9.68, 3.35 and 2.8 MPa, respectively.
- 7) According to experimental results, SBR cannot improve the mechanical properties of SBR-modified cement mortars with fly ash when the S/W ratio of SBR is less than 6.8%. Therefore, the lower bound on the S/W ratio of SBR-P for cement mortars with fly ash can be set at 6.8%.
- 8) The unit price of each material in Taiwan is used to calculate the cost (Cement is 4,000 TWD/ton, SBR-E is 130000 TWD/ton and SBR-P is 94500 TWD/ton). If the price of cement mortars with the W/B ratio of 0.5 without SBR and fly ash is set at 1.0, then the

price of the recommended SBR-modified cement mortars with fly ash is approximately 1.5. Therefore, the recommended SBR-modified cement mortars with fly ash is much cheaper than commercial polymer-modified cement mortars for the patch repair (around 10.0), and can be used to repair deteriorated RC members.

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