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Evaluating the bond strength between concrete substrate and repair mortars with full-factorial analysis

Kamile Tosun Felekoglu[1], Burcu Felekoglu*[2], A. Serdar Tasan[2] and Burak Felekoglu[1]

[1]*Civil Engineering Department, Dokuz Eylul University, Tinaztepe Campus, 35160 Buca, Izmir, Turkey*
[2]*Industrial Engineering Department, Dokuz Eylul University, Tinaztepe Campus, 35160 Buca, Izmir, Turkey*

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Abstract. Concrete structures need repairing due to various reasons such as deteriorative effects, overloading, poor quality of workmanship and design failures. Cement based repair mortars are the most widely used solutions for concrete repair applications. Various factors may affect the bond strength between concrete substrate and repair mortars. In this paper, the effects of polymer additives, strength of the concrete substrate, surface roughness, surface wetness and aging on the bond between concrete substrate and repair mortar has been investigated. Full factorial experimental design is employed to investigate the main and interaction effects of these factors on the bond strength. Analysis of variance (ANOVA) under design of experiments (DOE) in Minitab 14 Statistical Software is used for the analysis. Results showed that the interaction bond strength is higher when the application surface is wet and strength of the concrete substrate is comparatively high. According to the results obtained from the analysis, the most effective repair mortar additive in terms of bonding efficiency was styrene butadiene rubber (SBR) within the investigated polymers and test conditions. This bonding ability improvement can be attributed to the self-flowing ability, high flexural strength and comparatively low air content of SBR modified repair mortars. On the other hand, styrene acrylate rubber (SAR) modified mortars was found incompatible with the concrete substrate.

Keywords: repair mortars; concrete strength; surface roughness; surface wetness; polymer additives; full factorial experimental design

1. Introduction

From past to present, reinforced concrete is the most popular material used for structural construction purposes. Nevertheless, demand on concrete is increasing day by day in developing countries due to the ease of concrete production, availability and low cost of its material ingredients. However, reinforced concrete structures (in particular basements in contact with saturated soils, arch dams, concrete highways and tidal zone of marine structures) exposed to some deteriorative effects such as corrosion, sulfate attack, freezing and thawing, drying and wetting, alkali-aggregate reaction throughout their service life (Da Porto *et al.* 2011, Thomas *et al.* 2011,

*Corresponding author, Ph.D., Email: burcu.felekoglu@deu.edu.tr

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2012). In addition to these durability problems, incorrect design, overloading and poor quality of workmanship may generate repair, maintenance and strengthening requirements. Structures near the end of their service life, in other words, old buildings are more prone to these kinds of problems. Concrete cracking and cover loss arising from previously mentioned deteriorative effects should be repaired to maintain the structural integrity. In this section, a brief literature survey is presented under the following subtitles:

1.1 Application flexibility

Repair mortars are widely used solutions for concrete repair applications. It is fair to say that the majority of materials used for repairing damaged concrete are a blend of cement mortar with (usually polymer-based) additives (Hewlett 1993). Many types of polymer modified repair mortars, which are suitable for different application purposes, can be found in the current construction market. They can be applied by simply trowelling or as shotcrete for vertical and ceiling repairs. Alternatively, they can be directly poured into required area by self-flowing in the case of horizontal repair applications (Do and Soh 2003). Various fresh mortar properties may be required for each type of application and addition of appropriate polymer may provide the required performance. Such combinations also minimize the problems of property mismatch that result from organic mixtures alone, which offset the inadequate adhesion of inorganics on their own (Hewlett 1993).

1.2 Types, advantages and disadvantages of polymer based additives

Redispersible polymer powders or latex emulsions frequently used to improve the flowability and water soluble polymers such as semi-synthetic or synthetic cellulose derivatives improve the water retention capacity of repair mortars at fresh state (Ohama 1997). Copolymers of styrene acrylate rubber (SAR), styrene butadiene rubber (SBR), polyacrylic ester (PAE), ethylene vinyl acetate (EVA) are commonly used polymers for repair mortar preparation in the form of powder or emulsion (Afridi *et al*. 2003, Ohama 1998). On the other hand, water soluble polymer addition, which improves the water retention capacity of cement mortar, also often results in a thickening and viscosity enhancing behaviour (Knapen and Van Gemert 2009). Cellulose derivatives such as hydroxypropyl-cellulose (HPC), hydroxyethyl-cellulose (HEC), methyl-hydroxyethyl-cellulose (MHEC) and polyvinyl alcohol (PVA) can be given as examples of commonly used thickeners (Kim *et al*. 1999, Patural *et al*. 2011).

Flexural and tensile strength improvement, crack susceptibility reduction, high adhesion on sub-structure, water tightness, freeze-thaw and acid resistance, chloride impermeability can be listed as advantages of using polymers at hardened state (Cabrera and Al-Hasan 1997, Ohama 1998, Beeldens *et al*. 2001, Mirza *et al*. 2002, Medeiros *et al*. 2009, Yang *et al*. 2009). The improvement in flexural and tensile strengths can be attributed to development of polymer films by the coalescence of polymer particles in powdered and aqueous polymer-modified mortars. Cement hydration products compactly join with each other due to the presence of interweaving polymer films, thereby forming a monolithic structure with improved mechanical and durability characteristics of mortars (Afridi *et al*. 2003). However, some side effects such as excessive air-entraining, set retardation or strength loss may be observed if polymers employed at high dosages (Odler and Liang 2003). An air-detraining agent can be used in combination with polymers (Kim and Robertson 1997, Wu *et al*. 2002). Incompatibility of cement with some polymer types may also cause problems. These problems may be solved by performing small scale pre-trials. In summary, selection of appropriate polymer type and dosage is a critical factor to manufacture a proper repair mortar for any application.

1.3 Effects of substrate properties on repair mortar performance

In case of a concrete repair application, the success of polymer incorporated repair mortar is not only dependent on mortar performance itself. A repair mortar should also be compatible with substrate in terms of strength, elastic modulus and dimensional stability (Mangat and O'Flaherty 2004, Beushausen and Alexander 2008). Additionally, determination of mechanical properties and surface condition of substrate (roughness and surface wetness) is mandatory in order to provide an effective interface bonding (Vaysburd *et al*. 2004, Courard 2005, Pattnaik and Rangaraju 2007). Since the mechanical and physical properties of repair mortar and substrate change with time, aging should also be considered as an influencing parameter on bond strength.

Garbacz *et al*. (2005) investigated the effect of concrete surface treatment on adhesion between repair mortar and substrate. Researchers applied several mechanical methods of concrete surface preparation such as grinding, sandblasting, shotblasting, hand- and mechanical milling to obtain various qualities of the surface concrete substrate. The quantification of surface roughness has been evaluated using mechanical profilometry. They concluded that creation of the adhesion in repair system is a complex phenomenon resulting from a synergic effect of the surface roughness of concrete substrate, the presence of microcracks in the near-surface layer and deteriorated grains of aggregate due to the power of the surface treatment as well as processing properties of the repair materials.

Free water on the substrate surface can increase the water/binder (w/b) ratio and lower the strength of a thin layer of repair material near the interface. A dry, 'thirsty' surface on the other hand is often considered to excessively absorb water from the repair material, resulting in a harsh mix that will have difficulties in creating interlock with the substrate, and depriving the overlay from water necessary for full cement hydration. Based on the above opinions, it is commonly specified that the concrete substrate should be wetted to saturated surface conditions prior to application of repair mortar (Beushausen 2010). However, conflicting results have been reported about the influence of surface pre-wetting before repair mortar application on bond strength. Silfwerbrand (2003) and Beushausen (2010) reported that pre-wetting the substrate surface to a saturated surface condition has no beneficial influence on the bond strength between substrate and overlay (concrete or mortar).

1.4 Aging effect on bond strength between substrate and repair mortar

Theoretically, an improvement in bond strength between substrate and repair mortar with time can be expected since the amount of hydration products increases at the interfacial zone. Experimental studies conducted by Qiao *et al*. (2010) confirmed that aging increased the tensile bond strength of repair application. However, there is another time dependent indirect effect on bond strength known as drying shrinkage. Drying shrinkage difference between substrate and repair mortar at restrained conditions may generate undesirable stress at the interface which will negatively affect the bond strength in the long term. From this point of view, polymers which reduce the drying shrinkage will be beneficial to sustain the bond strength throughout the service life (Asad *et al*. 1997).

1.5 Methods of bond strength measurement

Many different test methods such as pull-off, slant shear, bi-surface shear, splitting prism, and flexural bond have been proposed by various researchers to measure the interfacial bond strength between concrete and repair mortars (Momayez 2005, Al-Ostaz *et al*. 2010, Qiao *et al*. 2010) or concrete with steel rebar (Arslan and Durmuş, 2011). A brief and compact literature review on common bond strength test methods can be found in Beushausen and Alexander (2008). Among these methods, standardized pull-off test is frequently preferred for cement-based materials to measure adhesion (ASTM D4541). However, one limitation lies in the difficulty of interpreting the results. This difficulty is caused by the fact that not all failures occur at the interface (Cleland and Basheer 2007). Both adhesive and cohesive or mixed mode failures can be observed and results may be interpreted by observing failed sections (ASTM D4541).

In the light of literature survey, the most critical substrate parameters influencing the interface bond strength of repair mortars were found as surface roughness and wetness. However, concrete strength level is usually kept constant by previous researchers and not considered as an influencing factor. In this study, not only surface roughness and wetness but also concrete strength level of the substrate are investigated as factors influencing the interface bond strength of repair mortars. Additionally, effects of the age of the repair mortar as well as the existence of polymer additives on the interface bond strength of repair mortars are examined. A full-factorial experimental design is performed to investigate the main and interaction effects of five factors (i.e. strength level, surface roughness, surface wetness, age, polymer additives) on bond strength between concrete substrate and repair mortar. Design tailored repair mortars with specific characteristics are used since they can be more indicative while comparing the performance of different substrates. The bond strengths of each repair mortar – substrate combinations are determined by using an ASTM D4541 Type-V pull-off test machine. Test data were analyzed using analysis of variance (ANOVA) under design of experiments (DOE) in Minitab 14 Statistical Software (2004).

2. Full factorial experimental design

Factorial design is a statistical method for investigating the effects of multiple variables on a response. Factorial design allows combining the study of multiple variables in the same factorial experiment instead of investigating the effect of one variable upon one response. This is particularly important since one-variable-at-a-time approach does not allow to detect interaction effects where factorial experiments are the only way to detect these effects (Montgomery and Runger 2011). Full factorial design tests all possible conditions by running experiments at every combination of the factor levels (SAS Institute Inc. 2008). It shows both main effects of each independent factor and interaction effects which is the combined effect of two or more independent factors on the response variable. Factorial design can be used with both continuous factors and categorical factors. Continuous factors take any value on an interval while categorical factors have a discrete number of levels.

The aim of this study is to investigate the change in the bond strength between concrete substrate and repair mortar in response to the existence of polymer additives, changes in the strength level of the concrete, surface wetness, surface roughness and aging. A 5x4x2x2x2 full factorial experimental design is performed to analyze the effects of these five categorical factors and their interaction effects on the bond strength between the concrete substrate and the repair mortar. The factors and their respective levels are given below:

1. polymer additives (five levels): four repair mortar mixtures incorporating different polymer additives were employed. Three of them are applicable by trovelling (conventional repair mortars incorporating methyl-hydroxyethyl-cellulose (MHEC), ethylene vinyl terpolymer (EVT) and styrene acrylate rubber (SAR), fourth one is designed as a self-flowable repair mortar incorporating styrene butadiene rubber (SBR). A standard mortar mixture without any polymer addition was also prepared for comparison,
2. strength level of the concrete substrate (four levels): 5, 10, 20, 30 MPa,
3. surface wetness (two levels): dry, wet,
4. surface roughness (two levels): smooth, rough,
5. composite (repair mortar-concrete substrate) aging (two levels): 7 days, 6 months.

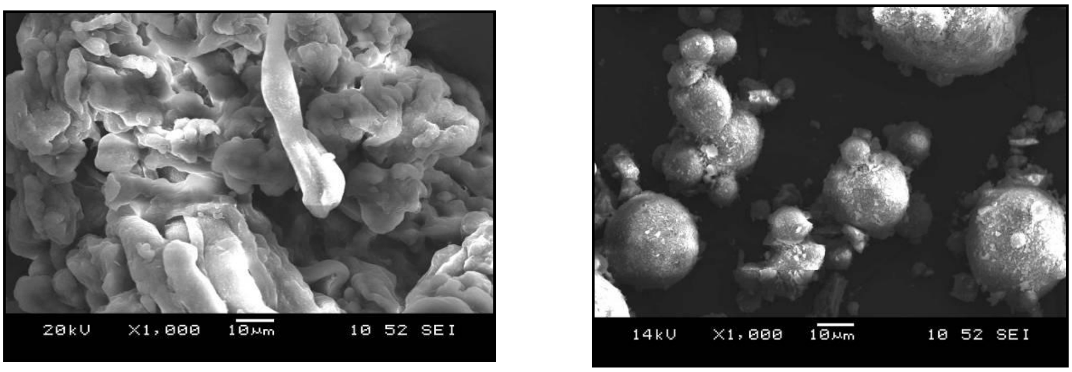
Repair mortar mixture proportions and test methodology will be explained in Sections 2.1 & 2.2 respectively.

2.1 Materials and repair mortar mixture proportions

An ordinary Portland cement (CEM I 42.5R) is used for both repair mortar and concrete substrate preparations. The Bogue composition of cement determined from X-ray fluorescence analysis (weight %), was: C_3S (66.99%), C_2S (2.96%), C_3A (8.01%), C_4AF (10.38%). The Blaine surface area and specific gravity of cement were 370 m^2/kg and 3.12 respectively. Standard sand conforming to the requirements of TS EN 196-1 was used.

Four different polymer additives have been used in order to prepare repair mortars for different applications which have been previously designed for different purposes (Tosun *et al*. 2012). The first one is a type of water soluble polymer (methyl-hydroxyethyl-cellulose - MHEC) which is frequently employed as a cohesion improving agent. The active ingredient of polymer is greater than 92.5% and minimum 70% of powder is under the size of 100 micrometers by weight. SEM micro-photographs confirmed that long irregular staple like MHEC particles embraced each other (Fig. 1a). This is possibly due to high molecular weight of MHEC. Solution of 1.9% MHEC increased the viscosity of water up to 8000-13000 mPa.s at 20^{o}C. Recommended dosage range of MHEC by manufacturers is %0.1-1.0 by weight of cement. Overdosing may cause excessive air entrainment and set retardation problems (Singh *et al*. 2003). Second polymer additive is a redispersible powder of ethylene vinyl terpolymer (EVT) which improves the workability of mortar by reducing the interparticle friction between aggregates and matrix phase. The SEM micro-photographs of these polymer particles presented in Fig. 1b confirmed that they are micro-spherical and particle size lies between 1-8 μm. Minimum film-forming temperature of EVT is 5^{o}C. The recommended dosage is 1-5% by weight of cement.

The physical and chemical properties of styrene acrylate rubber (SAR) and styrene butadiene rubber (SBR) latexes used in this study are presented in Table 1. These polymer emulsions are usually employed to improve the consistency of mortar and concrete at fresh state and improve the flexibility of brittle concrete at hardened state (Afridi *et al*. 2003, Wang *et al*. 2005). Additionally, both SAR & SBR improve the crack bridging ability and water resistance of concrete by film forming at hardened state (Odler and Liang 2003, Jenni *et al*. 2005). Low glassy transition and film forming temperatures make these latexes ideal for use in cementitious materials at ambient temperature conditions. The maximum dosage of latexes can be increased up to 30% for special



(a) (b)

Fig. 1 SEM micro-photographs of (a) MHEC particles, (b) EVT powders

C MHEC EVT SAR SBR

Fig. 2 Flow spread photographs of repair mortars

Table 1 The physical and chemical properties of polymer latex emulsions

Emulsion code	SAR	SBR
Solid content (% by weight)	57±1	48.5
pH value	7.0-8.5	8.0
Viscosity of emulsion (mPa.s) (ISO 3219 - shear rate: 25s^{-1} at 23^{o}C)	140-200	30
Glassy transition temperature (^{o}C)	-6	-5
Emulsion density (g/cm$^{3)}$	1.04	1.01
Emulgator type	anionic	mixture of anionic & non-ionic
Average particle diameter (micron)	0.2	0.15
Min. film forming temperature (^{o}C)	<1	<3
Tension strength of polymer film (N/mm^{2})	0.3	6
Elongation % of polymer film	>2500	1000

applications. In our study, SAR is used to prepare a repair mortar for trowelling application and SBR is used to prepare a self-flowable repair mortar.

According to the literature review, the mix proportions of most latex-modified mortars for various applications are in the range of the cement-fine aggregate ratio = 1/2 to 1/3 (by weight) (Ohama, 1995). In practice, lower cement-fine aggregate ratios are usually preferred due to economical reasons by providing minimum required strength. For this reason the cement-fine aggregate ratio (by weight) is kept constant as 1/3 for all mixtures. The W/C ratio and dosage of e ach polymer type, which were determined from preliminary experiments, are presented in Table 2.

Table 2 Mixture proportions of repair mortars and test results of some important properties

Repair mortar type	Polymer dosage	W/C	Flow spread value* (mm)	28d. compressive strength** (MPa)	28d. flexural strength** (MPa)	Air contents*** (%)
C (control mortar)	0	0.50	130	50.8	9.3	4
MHEC	0.25%	0.60	134	24.3	5.3	10
EVT	3%	0.52	132	45.8	8.7	12
SAR	%10	0.44	129	43.4	10.8	11
SBR	%10	0.50	170	54.2	10.7	7

* Flow spread values have been determined by using a flow table conforming ASTM C230 standard. Note that no external energy is applied in case of self-flowable mixture.

** Compressive and flexural tests have been performed on 40 × 40 × 160 mm specimens conforming the ASTM C348 & C349 standards.

*** Air contents have been calculated by taking the difference between theoretical unit weight and measured fresh unit weight into account.

Mortar mixtures have been prepared with a Hobart mixer following the same mixing procedure: First, 675 g cement, 2025 g sand and if required powder additives (MHEC and EVT) dry mixed for 2 min. Mixing water and if required latex emulsions (SAR and SBR) were then added to the dry mix. Total mixing time was 5 min to ensure homogeneous mixing. The flow-spread values, mechanical properties and calculated air contents of repair mortars are also presented in this table. The flow spread values of repair mortar mixtures (C, MHEC, EVT and SAR) designed for trowelling applications were nearly constant (130 ± 5 mm), while the self-flowing spread value of SBR incorporated mortar was 170 mm. The difference between self-flowable mortar and other mixtures in terms of workability can be observed in Fig. 2. In addition to application easiness, self-compactability of repair mortars may bring considerable advantages such as improvement on both micro and macro pore filling ability on substrate surface without causing any segregation (Emmons *et al.* 1994). Furthermore, the increase in the contact area between substrate and overlay positively influence the bond properties. Segregation resistance of this highly flowable material arises from its optimized plastic viscosity (Domone and Jin, 1999). MHEC negatively affected the compressive strength properties possibly due to the increase in water demand. W/C ratio was increased from 0.50 to 0.60. On the other hand, other polymer additives slightly reduced the compressive strength due to air-entrainment with an exception (SBR). The low compressive strength of MHEC incorporated mortars may also be attributed to the relatively high W/C ratio of this mixture. In the case of SBR, better mechanical properties have been obtained despite 3% increase in air content compared to control mortar.

2.2 Concrete substrate preparation, repair mortar application and pull-off tests

Concrete mixture proportions, which were designed at four different strength levels, are presented in Table 3. The 28 days compressive strengths of very low strength (VLS), low strength (LS), normal strength (NS) and high strength (HS) mixtures were 5, 10, 20 and 30 MPa respectively. The slump values of concrete mixtures were in the order of 100-120 mm. Fresh

Table 3 Mixture proportions of concrete substrates

Concrete substrate strength levels	Cement (kg/m^3)	Limestone filler (kg/m^3)	Water (kg/m^3)	Fine aggregate* (0-5 mm) (kg/m^3)	Coarse aggregate* (515mm)(kg/m^3)
VLS (5 MPa)	156	156	287	864	732
LS (10 MPa)	230	100	263	859	729
NS (20 MPa)	299	-	225	973	826
HS (30 MPa)	350	-	177	790	1004

* Fine and coarse aggregates were crushed limestone.

Fig. 3 Homogeneously roughened concrete surface

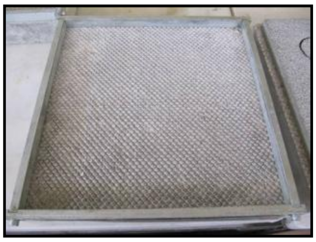


Fig. 4 15 × 320 × 320 mm molds to provide constant mortar thickness

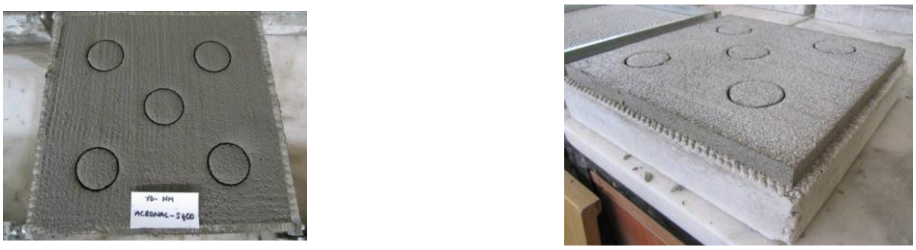


Fig. 5 Circular hole openings with 50 mm diameter on repair mortars after 7 days

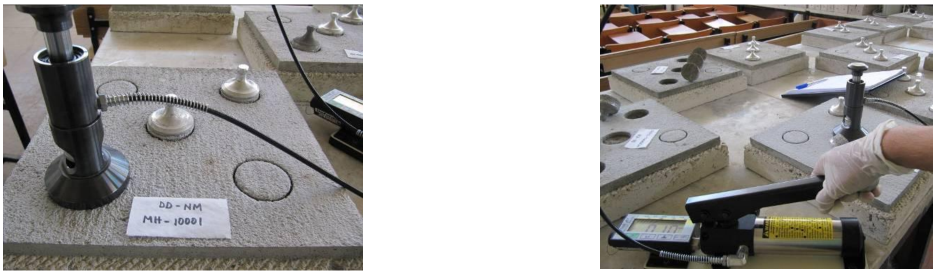


Fig. 6 Dollies and pull-off testing

Fig. 7 Preparation of hole openings with a core driller after 6 months

concretes have been casted into prismatic moulds of 50 × 350 × 350 mm. One side of each prismatic substrate (top side) is roughened with a special meshing and brushing methods described in Tosun *et al*. (2012). The surface roughness degree of all substrates is accepted as similar. A representative image after surface roughening process is presented in Fig. 3. The other side (bottom side) was smooth and no extra processing was performed. Bottom surfaces of formworks were covered with a polyethylene sheet to maintain a smooth surface. All concrete substrates were cured in lime saturated water for 28 days and dried in the laboratory before the application of repair mortars. Drying period before repair mortar application was 3 days.

Repair mortars have been applied onto concrete substrates with a constant thickness of 15 mm by using 15 × 320 × 320 mm steel molds (Fig. 4). For each substrate set, half of the concrete specimens were wetted before mortar application and saturated conditions have been obtained. The other half of substrates were kept dry. Control mortar and four polymer incorporated repair mortars have been applied onto substrate by using a trowel. Self-flowable mortar is just poured into the mold. Five circular holes with 50 mm diameter have been formed on repair mortars after surface finishing (Fig. 5). The first groups of pull-off tests have been performed 7 days after the repair mortar application. 50 mm diameter dollies have been stuck on repair mortars with a two-component epoxy resin. A pull-off machine conforming the ASTM D4541 Type V standards was used for pull-off tests (Fig. 6). The rate of loading was kept constant at 0.2-0.5 MPa/s. The same substrate-repair mortar combinations were used for pull-off tests at 6 months. Four new circular holes of 50 mm diameter have been formed by using a core-drilling machine (Fig. 7). The same pull-off testing procedure applied again.

3. Test results and analysis

3.1 Analysis of failure sections and visual interpretation

The failure sections of all specimens after pull-off test have been photographed and analyzed according to their mode of failure as substrate failure (Fig. 8(a)) or repair mortar failure (Fig. 8(b)). Most of the specimens exhibited mixed failure mode (failure section is composed of some part from mortar and some part from substrate – Fig. 8(c)). Some generalizations may be proposed based on these observations by neglecting the exceptions: Failure usually occurred from the substrate or between substrate and repair mortar overlay (Fig. 8(d): weak transition zone). In particular, the former behavior was mostly observed in the case of low strength substrates with

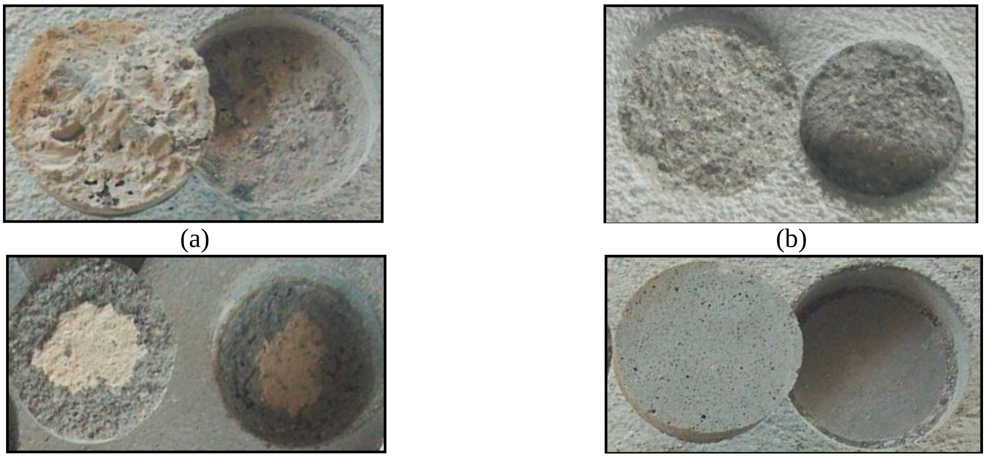


Fig. 8 Failure modes observed after pull-off tests in this study: (a) failure from substrate concrete, (b) failure from repair mortar, (c) mixed mode failure, (d) failure between substrate and repair mortar

smooth and dry surface conditions. The latter failure mode is more frequently observed when substrate strength is higher and surface is smoother. Finally, failure from repair mortar overlay rarely observed only in the case of low strength overlay repair mortar (MHEC) and high strength (HS 30MPa) substrate with wet and roughened surface conditions. In the light of these observations, it can be assumed that minimum bond strength of these repair mortars on related substrate have been obtained even though the full substrate failure is observed. It should be noted that these repair mortars potentially will have higher bond strength if applied on a higher strength substrate. In other words, if the location of failure is in the substrate, then minimum bond strength was obtained and potential bond strength of mortar on a higher strength substrate was not achieved.

3.2 Descriptive data

For descriptive purposes, 7 days and 6 months pull-off test results have been grouped into four sets according to the surface roughness and wetness of concrete substrates at four strength levels. For each set, the average bond strength between repair mortar and related substrate are plotted as bar charts with the standard deviations (Figs. 9 and 10). Due to the high number of variables in test conditions, it is hard to make generalizations with the resultant data on the pull-off strength behavior in these figures. It seems like there is an increase in bond strength values as the substrate strength is increased when a single repair mortar with definite surface properties is considered. However, there are exceptions which made the results difficult to interpret. When repair mortars are compared with each other at constant substrate strength and surface properties, highest pull-off strength results are usually obtained from the one prepared with SBR and the lowest pull-off strength results are usually obtained from mortars incorporating MHES or SAR. The relative performance of repair mortars changes depending on the substrate surface properties.

Even though some conclusions may be obtained from Figs. 9 and 10, factorial design is a necessary and emerging tool to statistically interpret the effects of multiple variables on a single response. By this way, the main effects of each independent factor and interaction effects, which is the combined effect of two or more independent factors on the response variable, can be obtained.

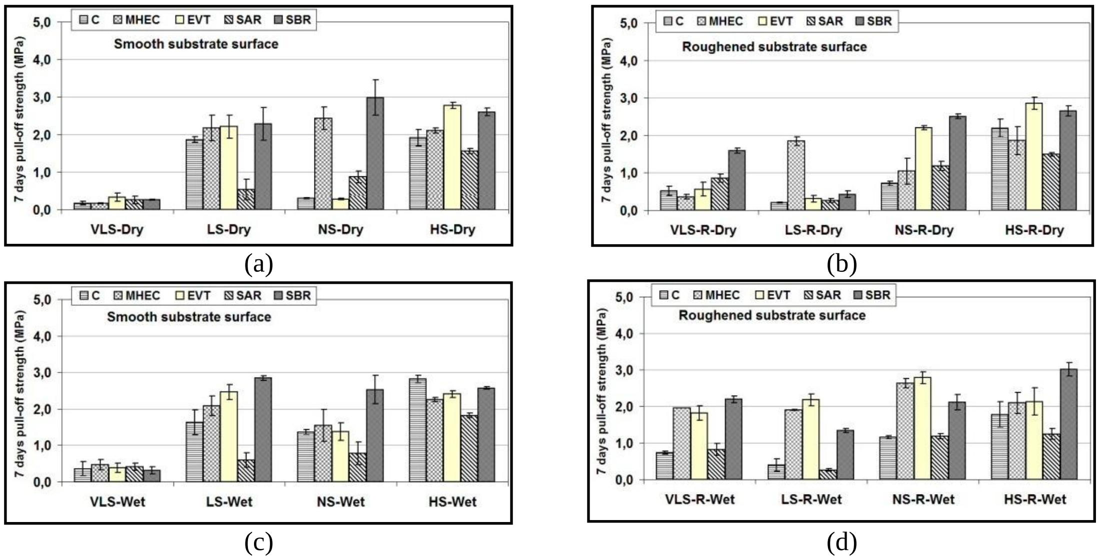


Fig. 9 Pull-off test results performed at 7 days. Repair mortars applied on; (a) Smooth and dry substrate, (b) Roughened and dry substrate, (c) Smooth and wet substrate, (d) Roughened and wet substrate

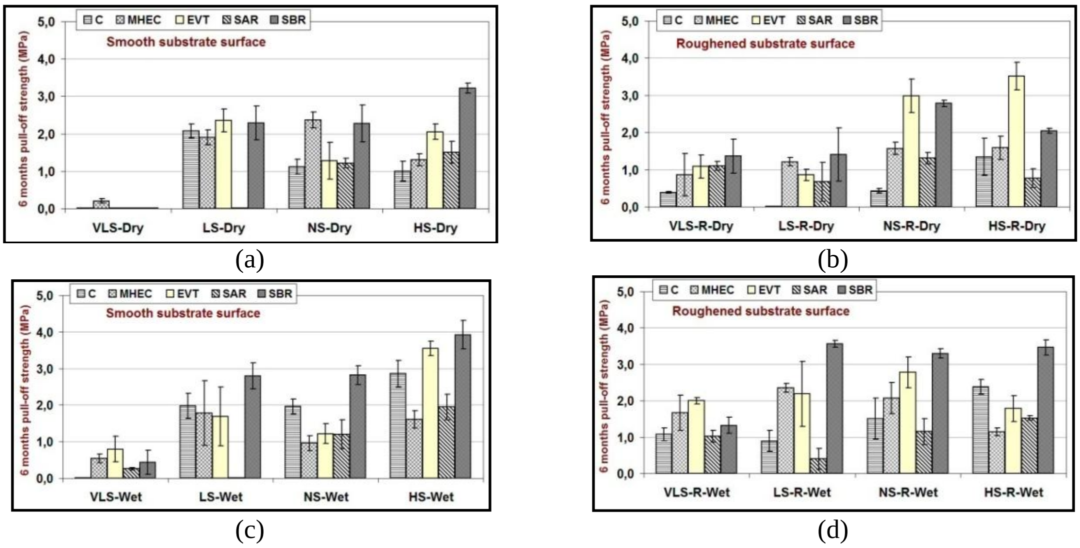


Fig. 10 Pull-off test results performed at 6 months. Repair mortars applied on; (a) Smooth and dry substrate, (b) Roughened and dry substrate, (c) Smooth and wet substrate, (d) Roughened and wet substrate

3.3 Full factorial analysis

The effects of five variables (i.e. surface roughness, surface wetness, aging, strength level of the concrete and polymer additives) on the interface bond strength between concrete substrates and repair mortars are investigated with full factorial analysis. ANOVA under DOE in Minitab 14 Statistical Software (2004) is used for this analysis.

Table 4 ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	2	12.594	12.594	6.297	187.48	0
Age	1	0.4744	0.4744	0.4744	14.12	0
Rough	1	0.8375	0.8375	0.8375	24.93	0
Wet	1	14.1763	14.1763	14.1763	422.06	0
Strength	3	131.9629	131.9629	43.9876	1309.62	0
Add	4	98.0974	98.0974	24.5243	730.15	0
Age*Rough	1	0.6848	0.6848	0.6848	20.39	0
Age*Wet	1	0.526	0.526	0.526	15.66	0
Age*Strength	3	1.651	1.651	0.5503	16.39	0
Age*Add	4	4.0267	4.0267	1.0067	29.97	0
Rough*Wet	1	1.6252	1.6252	1.6252	48.39	0
Rough*Strength	3	40.6872	40.6872	13.5624	403.79	0
Rough*Add	4	7.6925	7.6925	1.9231	57.26	0
Wet*Strength	3	0.8319	0.8319	0.2773	8.26	0
Wet*Add	4	3.5478	3.5478	0.8869	26.41	0
Strength*Add	12	33.0234	33.0234	2.752	81.93	0
Age*Rough*Wet	1	0.0191	0.0191	0.0191	0.57	0.451
Age*Rough*Strength	3	2.6162	2.6162	0.8721	25.96	0
Age*Wet*Strength	3	2.1474	2.1474	0.7158	21.31	0
Age*Rough*Add	4	0.2833	0.2833	0.0708	2.11	0.08
Age*Wet*Add	4	3.7323	3.7323	0.9331	27.78	0
Age*Strength*Add	12	6.4484	6.4484	0.5374	16	0
Rough*Wet*Strength	3	7.2172	7.2172	2.4057	71.62	0
Rough*Wet*Add	4	3.9895	3.9895	0.9974	29.69	0
Rough*Strength*Add	12	18.4925	18.4925	1.541	45.88	0
Wet*Strength*Add	12	12.1683	12.1683	1.014	30.19	0
Age*Rough*Wet*Strength	3	1.4593	1.4593	0.4864	14.48	0
Age*Rough*Wet*Add	4	1.7093	1.7093	0.4273	12.72	0
Age*Rough*Strength*Add	12	7.2228	7.2228	0.6019	17.92	0
Age*Wet*Strength*Add	12	4.0498	4.0498	0.3375	10.05	0
Rough*Wet*Strength*Add	12	11.8159	11.8159	0.9847	29.32	0
Age*Rough*Wet*Strength*Add	12	3.5002	3.5002	0.2917	8.68	0
Error	318	10.681	10.681	0.0336		
Total	479	449.9918				
S = 0,183271 R-Sq = 97,63% R-Sq(adj) = 96,42%						

The ANOVA test results are given in Table 4 with degrees of freedom (DF), sequential sum of squares (Seq SS), adjusted sum of squares (Adj SS), adjusted mean squares (Adj MS), F value and the corresponding p-values (P).

R-Square (R-Sq) value given at the bottom of the table shows that these variables and their interactions are able to explain 98% of the variation in the interface bond strength between concrete substrate and repair mortar. Table 4 gives a summary of the main effects and interactions. All the effects shown in this table are significant at $\alpha = 0.05$ level (p - value < 0.05), except these two 3-way interactions: aging-roughness-wetness and aging-roughness-polymer additives.

For better interpretation of the results, main effect and 2-way interaction plots are obtained. Fig. 11 illustrates the main effects plot of five variables on the interface bond strength between concrete substrate and repair mortar. In these graphs, values on the y-axis refer to the mean interface bond strength between concrete substrate and repair mortar. Values on the x-axis refer to the following:

- Composite (repair mortar-concrete substrate) aging: **Age** = {1, 2}; 1 = 7 days old composites, 2 = 6 months old composites,
- Surface roughness of the repair mortar: **Rough** = {1, 2}; 1=smooth surface, 2 = rough surface,
- Surface wetness of the repair mortar: **Wet** = {1, 2}; 1=dry surface, 2 = wet surface,
- Strength level of the concrete: **Strength** = {1, 2, 3, 4}; 1=VLS (5MPa), 2 = LS (10MPa), 3 = NS (20MPa), 4 = HS (30MPa),
- Existence of polymer additives in the repair mortar: **Add** = {1,2,3,4,5}; 1 = No additive, 2 = MHEC , 3 = EVT, 4 = SAR, 5 = SBR.
- As seen in Fig. 11, the effects (slopes) of aging and roughness on the interface bond strength are small. When compared to aging and roughness the effect of wetness is larger. The effect of strength level of the concrete is much larger. It looks like applying repair mortar on concrete with high strength level will produce better bond strength. Similarly, applying repair mortar on concrete with wet surface will produce better bond strength. When the effect of repair mortars with different polymer additives are compared, it can be seen that using SBR provides the highest bond strength; this is followed by EVT and MHEC. SAR has worse effect than using no additive. It can be concluded that SAR modified mortars was found incompatible with the concrete substrate from the viewpoint of bond strength. In addition to these main effects, understanding and interpreting combined effects of these variables is also important.

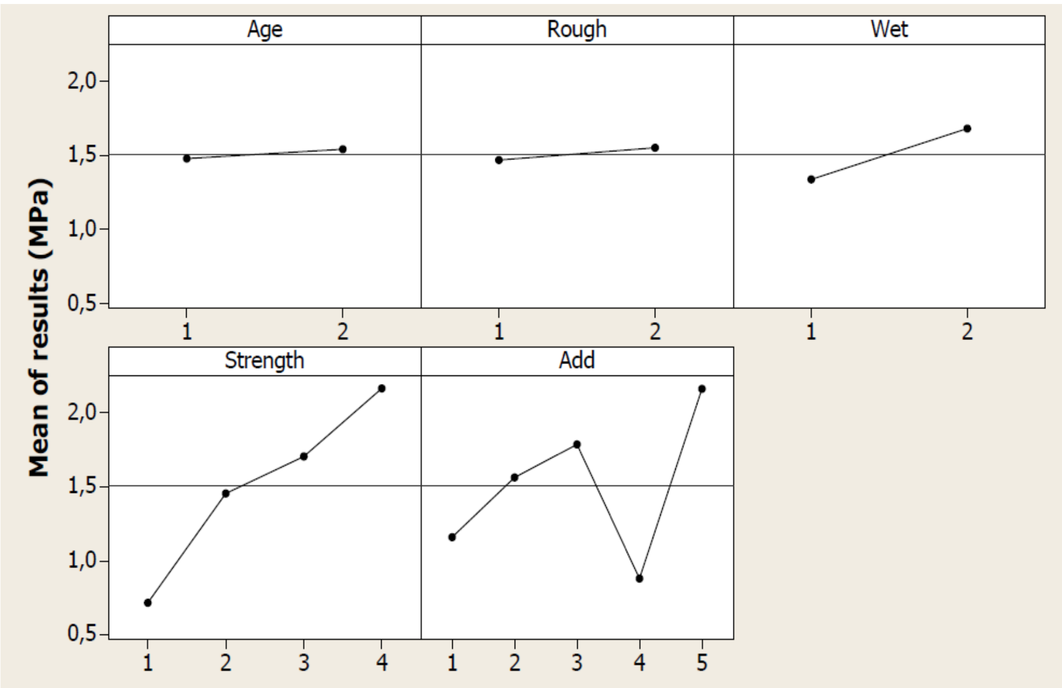


Fig. 11 Main Effects Plot (data means) for results

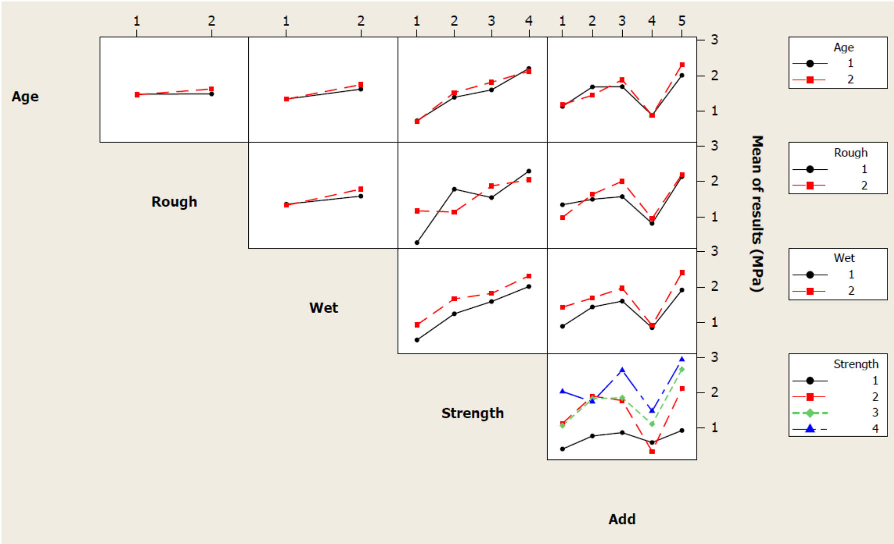
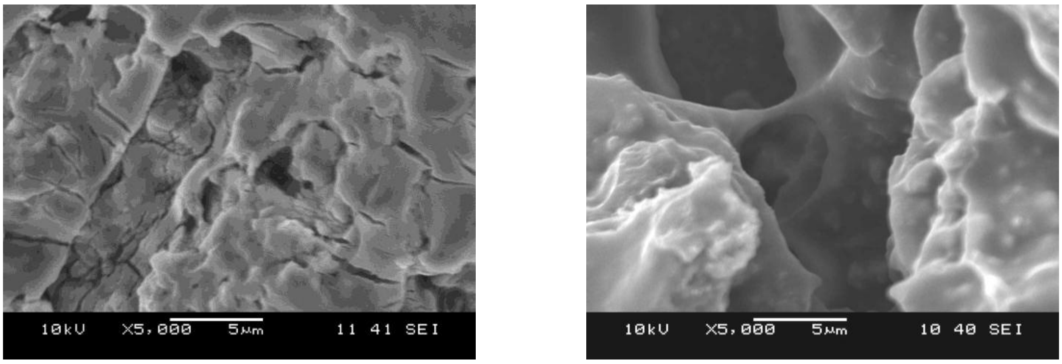


Fig. 12 Interaction plot (data means) for results



(a) (b)

Fig. 13 SEM images of aged repair mortars modified with (a) MHEC and (b) SBR

- Graphics in Fig. 12 show 2-way interactions of these five variables on the interface bond strength between concrete substrate and repair mortar. In these graphics, values on the y-axis again refer to the interface bond strength between concrete substrate and repair mortar. Values on the x-axis refer to the levels of the respective variables.

Interactions occur when the effect of a factor on the response differs depending on the level of another factor being tested. The graphs A, B, E show a very slight increase in the interface bond strength between the repair mortar and concrete substrate under increasing values of aging-roughness, aging-wetness, and roughness-wetness, respectively. Since the dotted and continuous lines intersect each other in each of these three graphs, we can say that there is interaction between aging and surface roughness, aging and surface wetness, and surface roughness and surface wetness. However, these interactions are very weak possibly due to the scatter of test results. It can be concluded that the effect of roughness on the interface bond strength slightly increases when the composite is more aged. Similarly, the effect of wetness on the interface bond strength slightly increases when the composite is more aged. The effect of wetness on the interface bond strength also slightly increases when the substrate surface is roughened.

In graph C, a weak interaction between the strength level of the concrete and aging is observed. Aging supports the positive effect of increasing strength level of the concrete on the interface bond strength until the strength level of the concrete reaches its maximum. Graph H confirms the positive main effects of both strength level of the concrete and surface wetness on the interface bond strength. However, with the increasing strength level of the concrete, the positive effect of wetness shows a slight decrease. Positive role of water as a curing agent at substrate confirmed with these findings.

There is a strong interaction between surface roughness and the strength level of the concrete as seen in graph F. For concrete substrates having very low and normal strength, having rough surface has a positive effect on the interface bond strength. However, for concrete substrates having low and high strength, having smooth surface has a positive effect on the interface bond strength. This complex interaction encourages further study on the combined effect of strength level of the concrete substrate and surface roughness.

Graphs D, G, I and J show the combined effects of polymer additives with other factors and need individual interpretation for each polymer additive. As seen in graph D, aging has a positive effect on the interface bond strength when EVT and SBR additives are used in the repair mortar. However, when MHEC additive is used aging has a negative effect on the interface bond strength. Scanning electron microscope (SEM) investigations conducted on aged repair mortars prepared with MHEC and SBR also confirmed these findings. As presented in Fig 13a, aging caused cracks on MHEC polymer distributed over cements matrix. On the other hand, SBR polymer films still maintain their flexibility (Fig 13b). Polymer films elongated and bridge the matrix as shown with white arrow in this figure. Furthermore, aging has almost no effect on the interface bond strength when SAR additive or no additive is used. Roughness has a positive effect on the interface bond strength for all additive types. On the contrary, roughness has a negative effect when no additive is used as seen from graph G. Graph I shows that wetness has a positive effect on the interface bond strength for all cases except SAR additive. In line with graph J, for each concrete substrate strength level, the additives are given below in the order of decreasing effect on the interface bond strength:

- Very low strength: SBR, EVT, MHEC, SAR, no additive
- Low strength: SBR, MHEC, EVT, no additive, SAR
- Normal strength: SBR, EVT, MHEC, SAR, no additive
- High strength: SBR, EVT; no additive, MHEC, SAR.
- Analysis results revealed that SBR additive provided the highest interface bond strength for all strength levels of the concrete substrate. This enhanced behavior can be attributed to three different factors: Firstly, as presented previously in Table 2, SBR modified mortar is self-compactable (flow diameter: 170 mm). Comparatively lower viscosity of this mortar mixture was highly effective in filling the pores when poured on the substrate surface. Second, the flexural strength of SBR modified mortar is higher (10.7 MPa) then other modified mortars which improves the bonding ability. Third, the amount of solid connection area at the interface is expected to be higher due to lower air content (7%) of SBR modified mortar compared to other modified mortars. On the other hand, high amounts of air-entrainment were determined for repair mortars modified by MHEC, EVT and SAR respectively (Table 2).

4. Conclusions

In this study, the effects of surface roughness, surface wetness, aging, the strength level of the concrete and existence of polymer additives on the interface bond strength between repair mortar and concrete substrate were investigated. The interaction between these factors and their combined effect on the bond strength between substrate and repair mortar was evaluated by using a full factorial analysis. According to analysis results, both strength level of the concrete and surface wetness has positive effects on the interface bond strength. However, with the increasing strength level of the concrete, the positive effect of wetness shows a slight decrease.

Analysis of the results revealed that the most effective repair mortar additive in terms of bonding efficiency was styrene butadiene rubber (SBR) within the investigated polymers and test conditions. Pull-off strength value of 3 MPa was obtained from SBR modified mortar if applied to a high strength substrate (30MPa) with a wet and roughened surface at 7 days. Pull-off strength values as high as 3.5-4 MPa are recorded from these composites at 6 months. On the other hand, styrene acrylate rubber (SAR) modified mortars was found incompatible with the concrete substrate.

By this method, it is also possible to compare, arrange and interpret the role of individual polymer based additives and finally select the right additive from the view point of bonding efficiency at different substrate conditions. In conclusion, the most effective repair mortar additive in terms of bonding efficiency was SBR and this bonding ability improvement can be attributed to the self-flowing nature, high flexural strength and low air content of SBR modified repair mortars.

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