International Journal of GEOMATE, June, 2024 Vol.26, Issue 118, pp.41-48
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.118.4306
Geotechnique, Construction Materials and Environment

EXPERIMENTAL STUDY ON THE BOND STRENGTH BETWEEN REPAIR MORTAR AND CONCRETE SUBSTRATE

*Leandro Madeira Branco[1], Abel Fernandes[1], and Isamu Yoshitake[1]

[1]Graduate School of Sciences and Technology for Innovation, Yamaguchi University, Japan

*Corresponding Author, Received: 28 Nov. 2023, Revised: 24 April 2024, Accepted: 26 April 2024

ABSTRACT: Concrete is widely used in infrastructure projects worldwide, including Timor-Leste, a newly independent country struggling to advance its social and economic development. Concrete repair and rehabilitation are critical for extending its service life. The effectiveness of the repair depends on the strength of the bond between the repair material and the concrete substrate. This experimental study focused on the bond properties of ordinary performance cement mortar (OPCM) and polymer-modified cement (PMC) mortar and also examined the interfacial bond strength under tension, shear, and a combination of both. Slant shear and double shear tests were conducted to investigate the bond strength. The test results showed that the epoxy resin used as an interfacial bonder exhibited a lower bond strength than the other test parameters. The results obtained from the tests indicated that the expected interfacial bond strength was achieved between the repair material and concrete substrate using the proposed method. The use of OPCM in repairs is considered sustainable and applicable in countries where access to repair materials is difficult, as experiments have shown satisfactory results with existing repair materials and combinations.

Keywords: Ordinary Performance cement mortar, Polymer modified cement mortar, Surface roughness, Bond strength.

1. INTRODUCTION

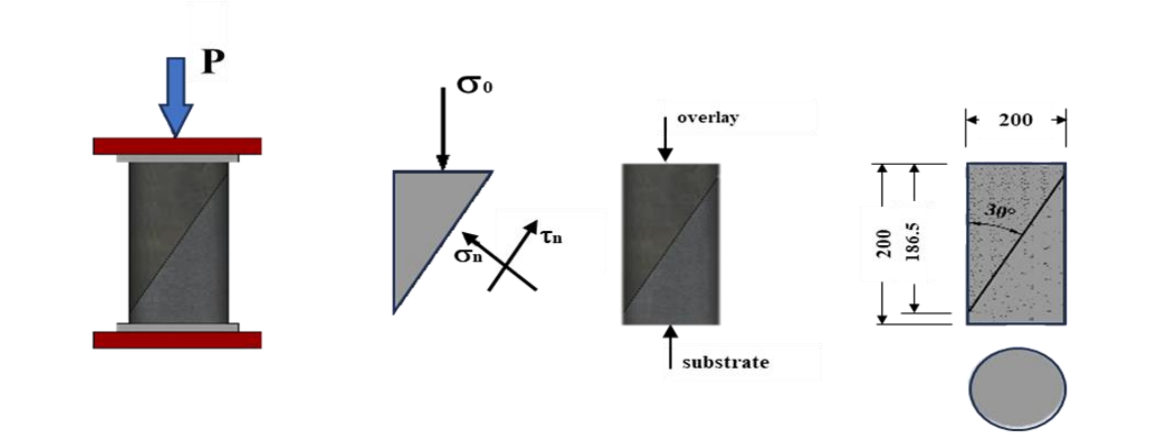
The Timor-Leste government is investing heavily in national development according to its national strategic development plan, in which all components of the development process, including infrastructure, are comprehensively addressed [1]. The government prioritizes a professional approach to all aspects of infrastructure to ensure quality of service and cost efficiency when maintaining its old and newly built facilities. Such facilities include bridges that have mostly been constructed using concrete materials requiring maintenance through repair to ensure the safety and extension of their service life.

Concrete is widely used in infrastructure projects worldwide, including in Timor-Leste, a newly independent country struggling to enhance its social and economic development [2]. However, concrete construction can deteriorate over time because of various factors, including environmental conditions, structural stress, and poor construction [3]. Concrete repair and rehabilitation involve problem-solving to extend the service life of existing structures. In the case of a repair system, the combination of properties between the repair material and the existing concrete substrate ensures that the combined system can withstand the applied stresses and maintain its structural integrity and protective properties in the specified exposure environment over the specified service life. The bond strength between the repair material and the existing concrete substrate is critical for the effective repair of damaged concrete. Furthermore, the bond strength between the concrete substrate and repair mortar (cement-based repair materials) is affected by the stiffness, substrate surface roughness, and surface angle [4-5]. Therefore, to ensure successful repairs, it is necessary to use appropriate repairing materials for adequate bond strength at the interface via considering the surrounding environmental conditions.

Numerous studies have investigated the bond strength of concrete repaired using ordinary performance cement mortar (OPCM) and polymer-modified cement (PMC) mortar. PMC mortars have gained popularity as repair materials owing to their superior properties, such as higher compressive and bond strengths, higher durability, lower permeability, and lower shrinkage rates [6-9].

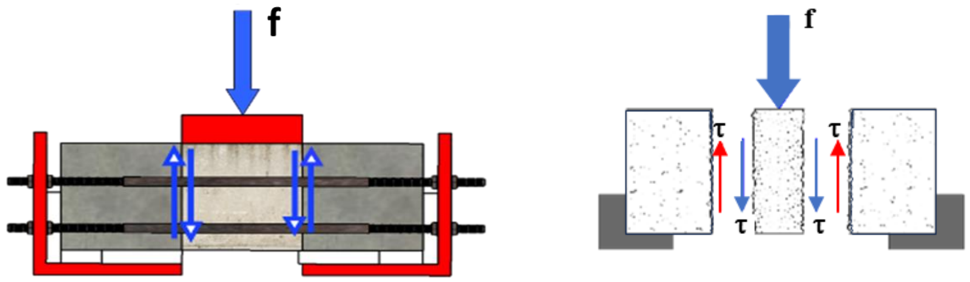
However, in Timor-Leste, a common option for repairing damaged concrete is a general mortar mixed with ordinary Portland cement (OPC), because of its marketing availability, benign application, and its applicability in general construction. This study investigated how a nonspecific repair material works in the repair of concrete by evaluating the bond strength between the interfaces in comparison to other options.

A mixed-design procedure was implemented for workability, and mechanical property examinations of the specimens were employed to obtain the optimum results. The surface area roughness of the specimen interface (concrete substrate) was determined by the size of the coarse aggregate, which was made visible by removing the cement mortar paste. The control methods included the OPCM, PMC



(a) Mechanics of testing (b) Cross-section (c) Specimen (d) Cross-section

Fig. 1 Slant shear test.



(a) Double shear test (b) Schematic of the specimen under shear stress

Fig. 2 Double shear test

mortar, and epoxy resin bonding of the repair materials.

This study experimentally investigated the correlation between repair materials that can be used and implemented in Timor-Leste and the available materials used for repair that have long-term durability. The study specifically examines the use of ordinary Portland cement (OPC) for OPCM and polymer-modified cement.

2. RESEARCH SIGNIFICANCE

Repairing is one of the actions undertaken to solve issues related to structures, as concrete has emerged as a popular construction material. In the present investigation using OPCM in conjunction with specifically designed material. The outcome not only unveils the suitability of OPC for repairment purposes but also underscores its pivotal role in bolstering the maintenance of repairment of reinforced concrete structures within the context of Timor-Leste. This is particularly significant given the limited designated repair material and economic constraints. The results can be emphasized by careful design and implementation.

The objective of this experiment is to investigate the performance of OPCM as a repair material and to determine its ability to maintain bonding with the concrete substrate under load. Through effective design methods and applications that increase strength, it is important to visualize the effectiveness by comparing a variety of repair material combinations, such as PMC mortar and epoxy resin bonding materials. The phases of the bonds in the repair system are represented by the concrete substrate, repair material, and boundaries.

Previous research has reported that the surface preparation of the substrate to be repaired is a critical element that encourages better adhesion [10-11] and the results emphasize the importance of efficiently improving the interfacial bond strength. This study evaluated the performance of the interfacial bond under tension, shear, and mixed compression, which can be attributed to the rough surface of the concrete substrate.

3. EXPERIMENTAL PROCEDURE

An experimental study was conducted by applying relevant methodologies to determine bond strength. Three main types of materials OPCM, PMC

Fig. 3 Slant shear sample

Fig. 4 Double shear sample

mortar, and epoxy resin bonding—were used and evaluated in combination. OPCM was used as an adhesive, water reducer admixture (to increase the workability and increase the strength of mortar) mixed with fine aggregate through a proper mixed design to achieve high-strength and PMC mortar with a standardized mixing procedure. Epoxy resin bonding was used as an interface border between repair materials and bonding between the OPCM and substrate concrete, and PMC mortar and substrate concrete [12]. The bond strength between the repair mortar and concrete substrate proved to be an essential aspect of this experimental study, which considered the durability of the repair material itself.

3.1 Slant Shear Test

The ASTM C882 and C1042 slant shear test schemes were first proposed in 1976 in the form of the Arizona Slant Shear Test, as shown in Fig. 1(a) [13]. The ASTM standard is often used as an experimental guideline in Timor-Leste. The slant shear test is a mechanical test used to evaluate the shear strength of a material or the bond strength at the interface or joint between two materials.

The application of an axial load to the specimens at an interface angle created a combination of shear and tensile stresses. Based on Fig. 1(b), the bond stresses were calculated as follows [14]:

$$\sigma_o = \frac{f}{A} \tag{1}$$

$$\tau_n = \frac{1}{2}\sigma_o \sin(2a) \tag{2}$$

$$\sigma_n = \sigma_o \sin^2 \alpha \tag{3}$$

where f denotes force (kN), A denotes the area of the specimen (mm^2), and σ_0 denotes the stresses applied on the specimen; σ_n and τ_n denote the interfacial normal and shear stresses (bond stress) on the bond plane resulting from σ_0, respectively; α denotes the slant shear angle.

The angle of the slant shear specimen was 30º–45° from the horizontal plane bonded to the substrate mortar specimen. In this study, the specimen as shown in (Fig. 1(c)) with the angle uses ± 30º (Fig. 1(d)) from the vertical axis to form a composite cylinder with a total composition of 100 mm in diameter and 200 mm in height.

After curing the substrate concrete specimen for 28 days and air-drying it for 7 days, use a hand of a slightly coarse brush (wire brush) to clean the concrete surface and remove any mortar or dust from the coarse aggregate. In addition, a paintbrush was used to ensure a thorough cleaning. Slant shear specimens were obtained by applying OPCM with and without epoxy, as well as PMC mortar, as shown in Fig. 3. The samples were cured 28 days before the experiment.

3.2 Double Shear Test

Double shear testing of concrete is a mechanical test method used to determine the shear strength of concrete specimens. The experiment study evaluates the capacity of a concrete specimen to resist shearing forces applied in two planes or along two parallel surfaces. A schematic of the double shear strength (shear friction test) is shown in Fig. 2(a) as an alternative double-plane shear test design, which was utilized by Tassios and Vintzeleou (1987) on pre-cracked unreinforced specimens, and a similar setup has been proposed by the Japanese Society of Civil Engineering (JSCE) for uncracked fiber-reinforced concrete specimens (JSCE 1990) [15].

Fig. 5 Surface roughness preparation for slant shear test

Fig. 6 Surface roughness preparation for double shear test

Therefore, with no internal reinforcement applied to the experimental samples in this study, the samples directly exhibited shear friction properties in the joint area and assisted in the application of external shear stress. This type of test is essential for understanding the behavior of concrete under shear loads, which is crucial in the design and evaluation of concrete structures.

Based on Fig. 2(b), the shear stresses were calculated as follows:

$$\tau = \frac{f}{2A} \quad (4)$$

where f denotes applied force (kN), A denotes the contact area of the specimen (mm^2), and τ denotes the shear stresses applied on the specimen.

After preparing the substrate concrete for the double shear test, it was cured for 28 days and air-dried for 7 days, use a hand of a slightly coarse brush (wire brush) to clean the concrete surface and remove any mortar or dust on the surface from the coarse aggregate, use a paintbrush to ensure the cleaning of dust at the surface. Double shear specimens were obtained by applying fresh OPCM with and without epoxy, as well as PMC mortar, as shown in Fig. 4. This procedure was implemented to guarantee the precision of measurements and test outcomes. The double-shear samples were cured for 28 days before the experiment.

3.3 Surface Roughness

The surface roughness of the concrete substrate is considered a key factor in the bonding performance between the concrete substrate and the cement-based repair mortar [16].

A rough surface provides a larger surface area and mechanical interlocking for the repair mortar to adhere, resulting in a more durable and enduring connection [17]. The rough surface in this experiment for the concrete substrate was acquired by spraying water over the concrete surface after casting the concrete to delay the hardening of the concrete and removing the soft concrete surface by brushing until coarse aggregates were exposed, as shown in Fig. 5 and Fig. 6 for double shear specimens and slant shear specimens, respectively. The samples were cured for 28 days before the experiment.

4. MATERIALS

4.1 Substrate Concrete

Substrate concrete refers to the underlying or existing layer of concrete that contains additional materials, such as coatings, overlays of repair mortars, or new concrete layers. Furthermore, it serves as the base or foundation for these additional materials.

The substrate concrete utilized OPC with a density of 3.15 g/cm^3, fine aggregates (sea sand) with a density of 2.6 g/cm^3, water with a density of 1 g/cm^3, crushed gravel (5–20 mm) with a density of 2.71 g/cm^3, and a water reducer admixture with a density of 1.02 g/cm^3. Table 1 shows the substrate concrete composition, which was determined using the American Concrete Institute (ACI) method for mix design [18], mix design with a water-cement ratio (w/c) of 0.5. The ACI mix design method is generally used in Timor-Leste. The concrete was cast, combined the fine aggregate and cement were in the mixer. Then, add an admixture (water reducer) to the water. Next, add half of the water mixture to the mixer. Followed by the coarse aggregate and the remaining water mixture. The mixing process was allowed for three minutes before being discharged from the mixer for placement in the form. The mixer was continuously operated throughout the mixing procedure. The molds were formed in different shapes depending on the purpose of testing: a rectangular form with dimensions (100 mm × 100 mm × 70 mm) for double shear and a

Table 1. Mix proportion of concrete substrates

Mix	w/c (%)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water-reducing agent (kg/m^3)	Air content (%)	Slump (cm)
Substrate concrete	50	170	340	741	1067	3.4	4.2	6

Table 2. Mix proportions for repairing materials.

Mix	w/c (%)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Water-reducing agent. (kg/m^3)	Flow (mm)
Ordinary Performance cement mortar (OPCM)	30	210	700	1354.4	7	150
Polymer-modified cement (PMC)		252	1850	-	-	147

cylindrical prismatic form with an angle of 30° for slant shear including cylinder specimens for the compressive strength (diameter 100 and height 200 mm). The samples were cured for 28 days before the experiment.

4.2 Ordinary Portland Cement Mortar

OPCM is an important construction material for plastering and repairing due to its excellent bonding properties, strength, versatility, and affordability in various construction applications. It is widely used in the construction industry in Timor-Leste.

This investigation utilizes OPC with a density of 3.15 g/cm^3, fine aggregates (sea sand) with a density of 2.6 g/cm^3, water with a density of 1 g/cm^3, and water reducer admixture with a density of 1.02 g/cm^3 for cement mortar mixtures. The cement mortar was designed with a water-to-cement (w/c) ratio of 30%, and a mixing ratio of 1:2.2 by volume as shown in Table 2.

In the mixing procedure, fine aggregates and cement were added to the mixer followed by admixture and water, the mixing process was allowed for three minutes before being discharged. Prepare sample for compressive strength (diameter 50 mm and 100 mm height), slant shear, and double shear.

In addition, all specimens for compressive strength, slant shear, and double shear strength tests were cured for 28 days to ensure proper strength development.

4.3 Polymer-Modified Cement Mortar

PMC mortars are important construction materials owing to their exceptional properties. The excellent characteristics of this substance make it a widely favored option for repairing damaged concrete.

The typical repair cement mortar used in this study for polymer-modified cement is a commercial PMC (RepairmixJ1 produced by Tokuyama Company, Japan), which is a form of repair material for concrete structures.

PMC is composed of a combination of Portland cement (which contains crystalline silica), silica sand (which contains silica, aluminum oxide, and iron oxide), admixtures (which contain calcium oxide), and fibers. The PMC mortar mix proportions were based on the manufacturing guidelines, as shown in Table 2. The mixing process was allowed for three minutes before being discharged. Prepare samples for compressive strength testing with a diameter of 50 mm and a height of 100 mm, as well as for slant shear and double shear tests.

Furthermore, all specimens designed for testing the compressive strength, slant shear, and double shear strength were properly cured for 28 days to guarantee optimal strength development.

4.4 Epoxy Resin

Epoxy was employed in this research functions as a part of the specimens and interface connection between the substrate concrete before pouring the repair materials onto the surfaces. Epoxy resins are generally created through the combination of two or more substances, such as an epoxy resin and a hardener, before being applied. In particular, we used the epoxy resin XL-800 (Epotherm®), where the main agent and hardener of XL800 were mixed in a weight ratio of 4:1, and the density was approximately 1.10–1.30 g/cm^3. The laminating epoxy (XL800) was manufactured by Mitsubishi Chemical Institute Co., Ltd. The mechanical properties provided by the manufacturers are listed in Table 3.

Table 3. Mechanical properties of epoxy resin

Properties	Epoxy resin (MPa)
Tensile strength	≥ 30
Flexural strength	≥ 40
Lap shear strength	≥ 10
Bond strength to concrete	≥ 1.5

5. RESULTS AND DISCUSSION

5.1 Physical Properties of Materials

The ASTM C39 standard test method was used to determine the compressive strength of the cylindrical samples of substrate concrete [19] and the ASTM C109 standard test for compressive strength of the OPCM and PMC mortar samples [20]. Following a 28-day curing period, compressive strength tests were conducted on the samples of repair materials and concrete substrates in the laboratory.

The three different types of materials resulted in different strength outcomes that correlated with the designed w/c ratios. The graph in Fig. 7 displays the average compressive strength for OPCM and PMC mortar, as well as substrate concrete, with OPCM having the highest strength at 71.08 MPa, followed by PMC mortar at 44.8 MPa, and substrate concrete at 31.06 MPa.

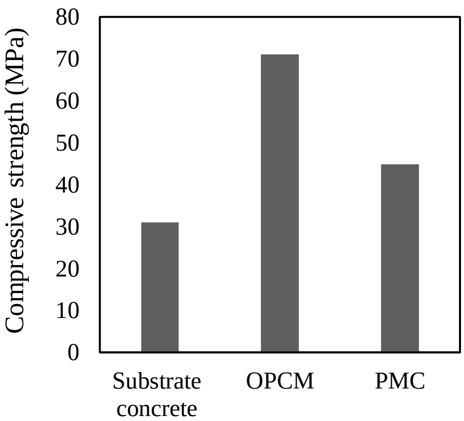


Fig. 7 Compressive strength of materials

5.2 Slant Shear

The interfacial bond properties between the concrete substrate and repair materials are determined by two forces: the slant shear and compressive strength as shown in Fig. 8.

Table 4 displays the surface compressive strength results of the sample, as well as the slanted shear and tensile strengths that occurred at the interface of the substrate concrete with the repair materials. The test conducted for this specific experiment also resulted in the compressive strength of the same specimen, which was calculated using Eq. (1). The compressive strength of the joint between the concrete substrate and the PMC mortar was 34.41 MPa. However, when both surfaces were treated with epoxy resin, the strength decreased by 35% to 23.75 MPa. Similarly, the compressive strength of the concrete substrate and OPCM joint sample reached 37.95 MPa, which also decreased significantly when treated with epoxy resin on the joint, reaching only 19.56 MPa.

Fig. 8 Slant Shear experiment

The results obtained from the compressive stress on the surface of the cylindrical specimen caused slanted shear and tensile stresses on the surface of the rough joint of the concrete substrate with the repair material. The bond strength calculations conducted on the repair materials used at the concrete substrate interface, obtained by Eq. (2), show that the bond strength of the PMC mortar is 14.9 MPa, while that of the concrete interface with epoxy resin and PMC mortar is 10.3 MPa on average. The OPCM maintained the highest strength of 18.0 MPa, while the slant shear strength decreased significantly to 8.5 MPa when combined with epoxy resin. The tensile strength calculations performed on the repair materials used at the concrete substrate interfaces, as obtained by Eq. (3), showed that the PMC mortar had a strength of 8.6 MPa, while that using epoxy resin and PMC mortar had a strength of 5.9 MPa.

Table 4. Mechanical properties of slant shear

Description	Compressive strength (MPa)	Slant shear (MPa)	Tensile strength (MPa)
PMC mortar	34.41	14.9	8.6
PMC mortar + Epoxy	23.76	10.3	5.9
OPCM	37.95	18.0	9.4
OPCM + Epoxy	19.56	8.5	4.9

Meanwhile, the OPCM maintained the highest strength of 9.4 MPa, and its tensile strength decreased to 4.9 MPa when combined with epoxy resin.

5.3 Double Shear Strength

The specimens produced at the vertical interface were tested against a single axial load. The bonding properties between the concrete substrate and repair materials are shown in Fig. 9 and the experiment result as shown in Table 5.

Fig. 9 Double shear strength test

Table 5. Experiment results of Double shear strength

Type Specimen	Load		Double shear strength
	kg.f	N	MPa
PMC	16480	161504	8.0752
	18800	184240	9.212
	14400	141120	7.056
OPCM	17280	169344	8.4672
	17160	168168	8.4084
	19400	190120	9.506
OPCM + Epoxy	8850	86730	4.3365
	10160	99568	4.9784
	11600	113680	5.684

The samples were calculated following Eq. (4), where the average result of double shear of substrate concrete bonded with PMC mortar achieved a strength of 8.11 MPa, and the mechanical properties rose by 8.79 MPa for bonding of OPCM. However, the surface of the concrete substrate with epoxy resin and cement mortar resulted in the lowest strength of only 5 MPa. The average bond strength test results demonstrate that PMC mortar and OPCM have high strength compared to epoxy mixed with repair mortar, as shown in Fig.10.

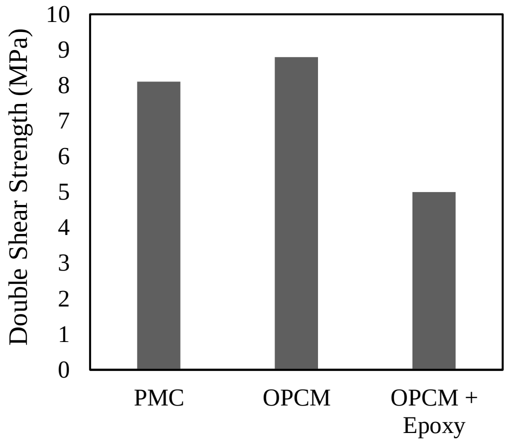


Fig. 10 Average double-shear strength

6. CONCLUSIONS

In this study, the mechanical properties of the bonding interfaces between repair materials consisting of OPCM, PMC mortar, epoxy resin bonding, and a concrete substrate were investigated. The experiments involved compressive strength, double shear, and slant shear tests. Several significant influencing factors were compared. The findings and conclusions are summarized as follows.

1. This study emphasizes the significance of bond strength between the repair mortar and the existing concrete substrate for effective repair and rehabilitation of concrete structures in Timor-Leste.
2. Incorporating epxy resin bonding to repair materials and concrete substrates results in a lower strength compared to other options due to the degree and time of applying the epoxy resin.
3. The use of OPCM for repair is considered sustainable because the experiment showed satisfactory results when applying OPCM compared to the other types of materials and combinations.

The experimental study shows how OPC can be utilized for bonding concrete surfaces and emphasizes the necessity of further research to implement this method for repairing damaged reinforced concrete structures. Future studies are important to analyze the effect of weather conditions, temperature, and durability of OPCM as a repair material on the bond strength in connection with deteriorated reinforced concrete structures exposed to the environmental conditions of Timor-Leste.

7. REFERENCES

[1] Republic Democratic of Timor-Leste, Timor-Leste strategic development plan 2011 – 2030, pp.83-124.

[2] Japan International Cooperation Agency (JICA), and Nippon Koei Co., Ltd, The Project for the Capacity Development of Road Works pin The Democratic Republic of Timor-Leste, Final Report (4th Year), 2014, pp.38-70.

[3] Delatte N, Failure distress and repair of concrete structures, CRC Press, Woodhead Publishing Limited, UK, 2009, pp.3-31.

[4] Wall J.S, and Shrive N.G, Factors affecting bond between new and old concrete, ACI Materials Journal, Vol.95, No.2, 1998, pp.117-125.

[5] Morgan D.R, Compatibility of concrete repair materials and systems, Construction and Building Materials, Vol.10, No.1, 1996, pp.57–67.

[6] Mirzaa J, Mirzab M.S, and Lapointeb R, laboratory and field performance of polymer-modified cement-based repair mortars in cold climates, Construction and Building Materials, Vol.16, 2002, pp. 365–374.

[7] Mahyuddin R, and Amin A.T, Effects of different curing regimes on engineering properties of polymer-modified mortar, Journal of Materials in Civil Engineering, Vol.24, No.4, 2012, pp.468-478.

[8] Kaba, P., Sato, S., Yamamoto, M., & Takahashi, K. Influence of freezing and thawing conditions at initial age on the strength development of mortars. International Journal of Geomate, Vol. 22, No. 94, 2022, pp. 128–134.

[9] Zhang X, Dua M, Fanga H, Shia M, Zhanga C, and Wanga F, Polymer-modified cement mortars: Their enhanced properties, applications, prospects, and challenges, Construction and Building Materials, Vol.299, 2021, 124290.

[10] Ehsani M.M, Ramezanianpour A, and Rajaie H, Comparison of methods for evaluating bond strength between concrete substrate and repair materials, Cement Concrete Research, Vol.35 No.4, 2005, pp.748–757.

[11] Gomaa E, Gheni A, and ElGawady M.A, Repair of ordinary Portland cement concrete using ambient-cured alkali-activated concrete: interfacial behavior, Cement Concrete Research, Vol.129, 2020, 105968.

[12] Júlio E, Branco F, and Silva V, Concrete-to-concrete bond strength: influence of an epoxy-based bonding agent on a roughened substrate surface, Magazine of Concrete Research, Vol.57, No.8, 2005, pp.463–468.

[13] ASTM C882/C882M-20 Standard test method for bond strength of epoxy-resin systems used with concrete by slant shear.

[14] Austin S, Robins P, and Youguan P, Shear bond testing of concrete repairs, Cement Concrete Research, Vol.29, 1999, pp.1067–1076.

[15] JSCE (Japan Society of Civil Engineers). 1990. Method of test for shear strength of steel fiber reinforced concrete (SFRC). JSCE SF-6.

[16] Wua E, Ayindea O.O, and Zhoua G, Interface shear behaviour between precast and new concrete in composite concrete members: effect of grooved surface roughness, KSCE Journal of Civil Engineering, Vol.26, No.6, 2022, pp.2799–281.

[17] Manawadu A, Qiao P, and Wen P, Characterization of substrate-to-overlay interface bond in concrete repairs: a review, Construction and Building Materials, Vol.373, 2023, 130828.

[18] Steven H. K and Michelle L.W, Design and Control of Concrete Mixtures: The guide to applications, methods, and materials, Portland Cement Association 2011, 15th edition, pp 231-262.

[19] ASTM C39 Standard test method for compressive strength of cylindrical concrete specimens

[20] ASTM C109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars.