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Examination of the Compatibility of Various Geopolymer Mortars for Repairing Damaged Concrete

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ABSTRACT

This work investigated the compatibility of defective substrate concrete (SC) and synthesized ambient-cured sustainable geopolymer mortars (GMs). The research gap in this field is to synthesize single- or binary GMs that can be used to repair damaged concrete with the best compatibility results. The production of GM uses a variety of binders, particularly clay minerals and synthetic ingredients. In GM and concrete, these minerals are regarded as suppliers of silica and alumina. The aluminosilicate must be activated by the alkaline solution to produce geopolymer gel products through the geopolymerization process. The alkaline activator solution and binder (solid material) were clay mineral, silica fume (SF), styrene-butadiene rubber latex (SBRL), sodium hydroxide (NaOH), and sodium silicate (Na_2SiO_3). The clay mineral was calcined at four different temperatures to produce calcined clay (Cc550, Cc650, Cc700, and Cc750), respectively. Compressive strength (CS) testing and X-ray fluorescence (XRF) analysis were used to assess the properties of clay and clay-based GM. A maximum CS of 25.4 MPa was obtained for the synthesis of geopolymer using Cc700-based GM for 28 days. The results show that clay calcined at 700 °C (Cc700) is suitable for GM production. The compatibility between SC and six repair GM mixtures of S-Cc, S-CcL, S-SF, S-SFL, S-CF, and S-CFL was investigated. The effects of the various repair mixtures were measured by bond strength tests (slant shear), third-point loading tests, and the influence of repair GM mixtures on the CS of SC (crack repair method). The study confirmed that the mixture of SC repaired with a binary mix of Cc and SF modified with SBRL exhibited superior compatibility with SC; on the other hand, it had the maximum bond and flexural strength compared with other single and binary test mixtures. The presence of SBRL in the single and binary mixtures indicates a positive index that the compatibility of repair materials and damaged concrete has been improved.

1. INTRODUCTION

Cement is considered the main building material due to its durability and mechanical properties. Excessive energy use and a notable increase in environmental contamination have been connected to the production of ordinary Portland cement (OPC). The expanding world population and the resulting demand for infrastructure will cause a sharp increase in the output of fuels and Portland cement [1]. On the other hand, other sustainable materials include clay minerals including kaolin, attapulgite, and montmorillonite [2]. Kaolin is the type of clay that attracts the greatest interest for the production of geopolymers [3]. The kind of clay that holds the most interest for the manufacturing of geopolymers is kaolin. During thermal processing, kaolin transforms into metakaolin, a great source of alumina (Al_2O_3) and silica (SiO_2) [4]. Strong alkaline activators are combined with binders rich in silica and alumina to create the geopolymer.

There has been a noticeable difference in restoration costs as compared to new construction in recent years due to the increased necessity to maintain and repair modern repair materials. Current estimates place the amount spent on structures on maintaining and repairing older buildings in Europe at around 50% of the entire amount spent on building. As a result, the cost of restoration has nearly doubled over the past ten years, when it was estimated to be between 25 and 30% [5]. Binary mixes of fine aggregates, such as river sand, limestone, and crushed sand, have varying effects on the geopolymer mortars (GMs) flow, setting time, compressive strength (CS), and density, according to Clement et al. [6]. CS mixtures perform better in terms of CS and flow values. Additionally, the study demonstrates that LS, which is readily available, provides a cost-effective alternative, especially for regions with limited access to river sand. The impact of earthquakes has caused the building elements to develop large cracks, and low-strength repair mortars are usually used in the repaired structures. In order to mitigate this issue, the alternative is to produce single and binary substitute materials that might be utilized as geopolymer binders in structures that have been restored. As a result, the strength of geopolymer

repair materials comprising 8 M and 5% calcium hydroxide ($Ca(OH)_2$) was quite high when compared to other values. As a result, alternative geopolymer repair mortars with high compatibility that might be utilized for restoration were developed. As a result of this, single and binary mortars are regarded as an important application for building repair and strengthening [7].

Additionally, one of the most rapidly developing industries is concrete repair. Unfortunately, there is no definitive answer when it comes to how long a repair will last for structural and non-structural elements. When choosing repair materials, there are a number of important factors to take into account, including surface preparation, material application, building procedures, and inspection. Additionally, design components, repair material criteria, and the influence on the environment are all equally important. These interrelated factors must be considered while making plans for a long-lasting repair. Numerous early failures originating from various reasons have been found in recent examinations of bridge deck restorations and other structural issues. These elements consist of improper material selection for repairs, unsatisfactory construction, and insufficient concrete substrate characterization [8].

Therefore, to provide a long-lasting repair, the qualities of the substrate concrete (SC) must fit properly (having the compatibility adjective). Durability restoration has an impact on the state of the structure and interacts with the overall loads in addition to the basic components (material quality) of the repair materials [9]. Commercial repair materials with exceptional mechanical properties and bonding strength are commonly used for concrete repairs. Nevertheless, these amenities come at a high cost. Use less expensive materials with comparable properties in place of repairs [10]. Using a binary Portland cement combination to boost the strength of high-calcium fly ash geopolymer is very attractive. In addition to creating calcium silicate hydrate, heat from an interaction between Portland cement and water can aid in the geopolymerization process and enhance the development of strength [11]. In sandwich specimens, Hu et al. [12] examined the bond strength between geopolymer and mortar substrate and discovered that geopolymer had a stronger bond than a comparable Portland cement mixture. Songpiriyakij et al. [13] discovered that the binary geopolymer pastes composed of silica fume (SF) and rice husk ash had binding strengths that were around half as high as those of comparable repair epoxies. Geopolymer materials can therefore be used as an alternative bonding material for restorations due to their high bond strengths. Sandblasting is the best method for surface preparation, according to a number of researchers. The polishing effect is a consequence of sandblasting [14]. Chemical compounds can also be used to improve the surface roughness of the substrate. An acid etching technique is used to prepare the bond's surface, although careful washing is required to remove the $CaCl_2$ that is created when HCl reacts with $Ca(OH)_2$ [15].

Pacheco-Torgal et al. [16] reported on the increase in bonding. In comparison to traditional PC, alkali-activated binder exhibited superior bonding, as evidenced by the high tensile strength ratio that was recognized in 2006. It was also possible that the residual properties of mortar may be improved by adding calcium hydroxide and activating the alkali in recycled concrete. This provides information on surface bonds and fracture resistance. Therefore, a monolithic failure type resulted from cracks that penetrated the slant surface [17].

Clay is considered a significant source of silica and alumina in GM. Partially alkalinizing materials, primarily Ca and Si, activate the first type. This method creates a CSH gel. In the second method, an alkaline solution is used to activate a material mostly composed of Si and Al. This reaction leads to the creation of an inorganic binder during the polymerization process [18]. Potassium hydroxide, sodium hydroxide (NaOH), potassium silicate (K_2SiO_3), or sodium silicate (Na_2SiO_3) are the most commonly utilized alkaline activators for activating alumino-silicate or calcium silicate in solid materials. By producing calcium aluminum silicate hydrate (C-A-S-H), calcium silicate hydrate (C-S-H), or sodium aluminum silicate hydrate (N-A-S-H) gels, the alkaline solution activators help dissolve the ions of Al^{3+} and Si^{4+} from the source of alumino-silicate, increasing CS. When NaOH and Na_2SiO_3 are used together, the CS is greater than when NaOH is used alone [17]. Repair solutions that significantly rely on the precise adjustment of the binder-to-sand ratio were found to be the most successful FA-based GM formulations. According to the experiments, the ideal ratio is 1:2, which balances long-lasting bonding strength with high workability [19]. In contrast to some other clay minerals, like metakaolin, where the percentage of CaO is lacking, the chemical composition of clay minerals at different calcination temperatures contains CaO. However, the higher content of CaO in the composition of clay minerals or natural pozzolan results in higher CS due to the amount of CSH gel formation [20].

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 Geopolymer mortar materials

The raw clay material (density = 2.44 g/cm³) was provided. The X-ray fluorescence (XRF) analysis of SF and Cc's chemical composition is shown in Table 1. The alkaline activators used were NaOH pellets (d = 2.25 g/cm³) and Na_2SiO_3 solution (d = 1.75 g/cm³), which were purchased from QREC, SDN, Istanbul, Turkey.

Table 1. Chemical composition of calcined clay (Cc) and silica fume (SF) at different calcination temperatures using the X-ray fluorescence (XRF) technique

Oxides	Percentage Compositions				
	SF	Cc550	Cc650	Cc700	Cc750
SiO_2	85.6	48.7	48.1	50.9	47.4
Al_2O_3	2.8	11.7	13.8	12.6	10.8
Fe_2O_3	0.9	11.4	10.5	11.9	11.3
CaO	1.9	13.5	11.9	14.6	13.5
MgO	1.2	4.3	3.9	3.7	4.1
TiO_2	0.4	1.5	0.9	1.2	1.6
K_2O	2.5	3.5	3.1	3.5	3.5
P_2O_5	0.9	1.4	1.8	1.6	1.6
SO_3	1.3	0.9	0.8	0.9	0.8
LOI	1.1	1.5	1.4	1.6	1.3

The fine aggregate (sand) used in this study was natural river sand from the Alnibaee district of Iraq. Styrene-butadiene rubber latex (SBRL) is used as a polymer modifier in this investigation. SBRL is the elastic copolymerized result of butadiene and styrene. Usually, latex is included in mortar as a suspension polymer in water. The MOLUMER Company manufactured this polymer. The SF used was supplied by

QREC SDN, BHD, Istanbul, Turkey.

2.2 Substrate concrete materials

Ordinary Portland cement (OPC) (Mass Type I) was supplied by Hueme Cement Sdn. Bhd., Irbil, Iraq, and was used throughout this work. Table 2 displays the cement's characteristics.

Table 2. Properties of the cement

Properties	Result	Limits
Initial setting time (hrs: min.)	2:58	≥45 min
Final Setting time (hrs: min.)	4:50	≤10 hrs
Compressive Strength (N/mm^2)		
2 days	29.80	≥20
28 days	54.84	≥52.5
Soundness (mm)	2	≤10
Sulphate content SO_3%	1	≤4
Chloride %	0.3	≤1

The Najaf district of Iraq provided the crushed coarse aggregate, which had a maximum size of 15 mm. Gravel had a specific gravity of 2.65 and absorption of 0.63%. The sand was natural river sand from Najaf district, Iraq. The fineness modulus of sand was 2.8.

2.3 Experimental methods

2.3.1 Particle size and fineness

In this study, the fine aggregate's particle size was investigated by mechanical screening. It was passed through a 1.18 mm sieve after being retained on a 150 µm sieve. The characteristics of SF, calcined clay (Cc), and clay were identified using the laser diffraction particle size analyzer (Mastersizer/E).

2.3.2 Preparation of calcined clay

An electrically powered furnace was used to burn the clay raw material. The calcination process then started at temperatures of 550, 650, 700, and 750 ℃ to produce Cc550, Cc650, Cc700, and Cc750. Chemical composition of Cc550, Cc650, Cc700, and Cc750 was due to ASTM C109 [21].

2.3.3 Edge shape of repair

As shown in Figure 1, the obtuse-angled edge shape of the repair was used. The main purpose of using this type of shape was to delve into how edge shape affected the functionality of the repaired composite parts.

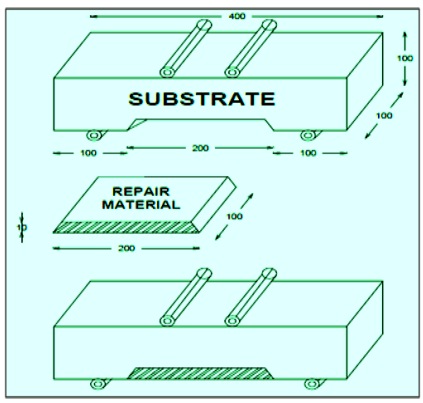


Figure 1. Obtuse angle edge

2.3.4 Compressive strength test

The CS test was conducted in accordance with ASTM C109 [21]. Steel cube molds of 50 × 50 × 50 mm. The CS of cubes was examined using a conventional testing apparatus with a 2000 kN capacity.

2.3.5 X-ray fluorescence

The elemental compositions were quantitatively measured using XRF.

2.3.6 Bond strength test

A total of 18 cylinders of Bond strength specimens were used in this test. Each mix type is the mean of three specimens. The bond strength of GM repair materials was determined using the standard ASTM C882 test procedure [22]. As shown in Figure 2, a composite cylinder was fabricated by casting SC. After demolding the molds (after 24 hours), the specimens of SC were completely immersed in water for 27 days. After that, the specimens were left inside the laboratory to dry for 7 days. Consequently, the specimens were cured at 70 ℃ for 24 hours and then allowed to cure at room temperature after the composite cylinder was demolded the following day. Compressive testing equipment was used to test the cylinder specimens. This test was conducted at an age of 63 days for SC (i.e., 28 days for repair GMs material).

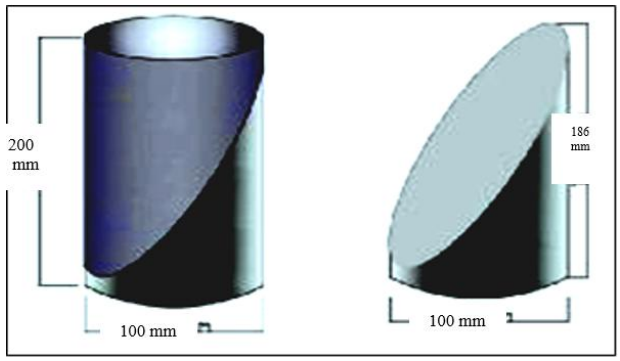


Figure 2. Composite section and substrate concrete (SC) for slant shear bond strength test

2.3.7 Third-point loading test (flexural strength)

A total of 21 prisms of flexural strength specimens were used in this test. Each mix type is the mean of three specimens. 100 × 100 × 400 mm prism specimens were used for the third-point loading test in accordance with the Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) [23]. A 50 kN LIYA SOILTEST-VERSA TESTER hydraulic machine was used. As seen in Figure 3, the prism's span length in this test method should be at least three times its depth. Consequently, the center third of the prism experiences the greatest amount of stress. This approach delivers the flexural strength known as the modulus of rupture, with a timber plate of (200 mm) length × (100 mm) width × (10 mm) thickness placed into the bottom of the composite prisms before casting. After casting and demolding the molds, a timber plate was removed, and the prisms were cured in water for 27 days. After that, specimens were left inside the laboratory to allow for drying for 7 days. The composite prisms (SC specimens batched with the repair materials) were demolded the next day. The third-point loading prism test was used to evaluate the prisms. For each substance, the average of the three specimens was noted throughout the test.

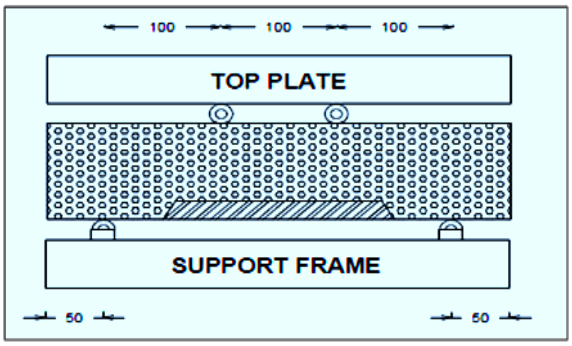


Figure 3. Measurement of flexural strength in the composite prism (All dimensions in mm)



Figure 4. The specimens after preparation and filling with the repair materials

2.3.8 Crack repair method

A total of 21 cubes of CS specimens were used in this test. Each mix type is the mean of three specimens. The mixes were molded, demolded a day after the SC was mixed, and then submerged in water to cure for up to 27 days. After being removed from the water, the samples were allowed to dry for seven days at room temperature [24]. At this point, the specimens were used to prepare surface cracks. The six repair materials (GMs) were then combined and applied. Washing, drying, and filling the cracks by gravity were the steps in the mending process. After that, the specimen was left for ambient curing. Figure 4 shows the specimens after preparation and filling with the repair materials.

3. DESIGN OF MIXTURES AND PREPARATION OF GEOPOLYMER MORTARS AND SUBSTRATE CONCRETE

3.1 Mix design of mixtures

Table 3 displays the repair GM combinations made for this investigation. Binder materials, fine aggregate, and an alkaline activator with a small amount of added water are all present in each GM combination. The CS can be improved by adding more binders to GM, but the setting times are decreased [25]. The repair material combinations modified with latex are shown in Table 4. The ratio of sand to binder was equal to 1.5 for all mixes [26].

Table 4 shows the mixture proportions of SC. The proportions of the concrete substrate mix were (1:1.6:2.5 by wt.), while the w/c ratio was 0.40.

3.2 Preparation of alkaline activators

Alkaline activators such as NaOH and Na_2SiO_3 solution mixes with additional water were employed in this study. One liter of solution, which represented the percentage of aqueous NaOH, was created by dissolving a similar quantity of NaOH pellets in distilled water. For 10 M, the corresponding mass was 404.0 g.

Table 3. Mix proportions of repair mixtures

Mix	Binder Materials (kg)		Styrene-Butadiene Rubber Latex (SBRL) (kg)	Sand (kg)	Na_2SiO_3 (kg)	NaOH (kg)	Added Water (kg)
	Cc	SF				Cc	
Cc550, 650, 700, 750	0.99	-	-	1.47	0.55	0.22	0.10
SF	-	0.96	-	1.45	0.39	0.15	0.04
CF	0.30	0.70		1.47	0.36	0.14	0.09
CcL	0.96	-	0.05	1.44	0.54	0.22	0.10
SFL	-	0.96	0.05	1.44	0.38	0.14	0.04
CFL	0.29	0.69	0.05	1.47	0.36	0.14	0.09

Table 4. Mixture proportions of concrete substrate

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	W/C	Water Content (kg/m^3)
Substrate Concrete (SC)	320	512	800	0.40	128

3.3 Mixing, casting, and curing of geopolymer mortar and substrate concrete

A Hobart bench mixer with a 4.73-liter capacity was used to mix the GM samples. First, two minutes were spent mixing the dry components (sand with binder). Prior to the solid substance being treated with the alkaline activator, it was prepared 24 hours in advance. They were blended for ten minutes to create the GM. Oil-coated steel molds measuring 50 × 50 × 50 mm were filled with two layers of fresh GM. A vibrating table was used to vibrate each layer for 15 seconds. After the curing time, the specimens were demolded and then placed in heat-resistant vinyl bags to stop moisture loss. After that, an oven set to 75 °C was used for 24 hours for the drying curing process [27]. In the mixer of SC, the dry constituents such as cement were placed to produce the concrete. Cement was placed between two layers of sand and then two layers of gravel. The dry ingredients were thoroughly combined for around 1.5 minutes to achieve a uniform mixture. After adding the required amount of water, the mixture was mixed for a

further two minutes to reach homogeneity. The SC mixture is then poured into the designated molds in two or three layers.

3.4 Repair materials (mixing, casting, and curing of specimens)

In all, six repair mixtures were employed in this investigation. The solid ingredients and fine aggregate were combined for two minutes in a dry state for GM mixes. After that, they were combined with water and alkaline activators. Second, the latex mixtures were combined for a further two minutes. Fresh GM was cast by bonding with the SC in 100 × 200 mm oil-coated steel cylinders for the bond test. For the 3-point loading test, the fresh 6 mixtures were applied to the obtuse angle area in the 100 × 100 × 400 mm prisms of SC. For the crack repair test, the 6 fresh mixtures were applied to the cracks made in the 150 × 150 × 150 mm cubes of SC. A vibrating table was used to vibrate the fresh repair materials for 15 seconds, as shown in Figure 5.



Figure 5. Preparation and casting of geopolymer mortars (GMs) repair materials and substrate concrete (SC)

4. RESULTS AND DISCUSSION

4.1 Compressive strength

The CS observations for OPM and Cc-based GM are shown in Table 5. It is evident that the oxide ratios and curing age have an effect on the CS. The CS in a mix (Cc550) improved from 17.9 MPa after three days of curing to 21.1 MPa after 28 days. The CS of a mix (Cc650) increased from 19.6 MPa after three days to 21.7 MPa after 28 days. The CS in a mix (Cc700) improved to 25.4 MPa after 28 days. Nevertheless, after 28 days, the CS of the Cc 750 increased from 21.6 MPa to 23.8 MPa. Table 5 displays the CS of GMs utilizing Cc calcined at various temperatures. The SiO_2/Al_2O_3 ratio determines how gradually the strength of Cc-based GM increases. Table 5 shows that the Cc700 mixture is greater than the Cc550, Cc650, and Cc750 mixtures. The CS increased by around 80% in overall strength at 28 days. Al_2O_3, which reacted more quickly than SiO_2, is linked to the early-age strength [28]. The SiO_2/Al_2O_3 ratio cannot remain constant during the geopolymerization process since it rises at different phases [29].

4.2 Chemical composition of Cc at various temperatures

The chemical analysis of clay and Cc550, Cc650, Cc700, and Cc750 was established by XRF analysis as shown in Table 1. For Cc550, Cc650, Cc700, and Cc750, the $SiO_2 + Al_2O_3 + Fe_2O_3$ in the C powders were 71.8%, 76.4%, 72.4%, and 72.5%, respectively, according to the data. Cc550, Cc650, Cc700, and Cc750 have SiO_2:Al_2O_3 molar ratios of 3.68, 3.45, 4.31, and 4.11, respectively. It was expected that when the activated clay's calcination temperature increased, the molar ratio would rise as well [30].

Table 5. Results of compressive strength (CS) of geopolymer mortar (GM)

Mix	Compressive Strength (MPa)			
	3 Days	7 Days	14 Days	28 Days
Cc550	17.9	19.8	21.1	21.1
Cc 650	19.6	20.3	20.8	21.7
Cc 700	23.1	23.4	23.7	25.4
Cc 750	22.6	22.2	23.4	23.8

4.3 Bond strength test and mode of failure

The results of the slant shear bond strength of composite specimens for the restoration of GM mixes, and SC cured at 63 days are displayed in Figure 6 and Table 6. As seen in Table 6, the mixtures containing SBRL have higher bond strength than the mixtures without SBRL, with a standard deviation (SD) equal to 0.208. This provides an index of the improvement of the bond between repair mixtures and SC. The bond between the repair materials and the underlying concrete in a repaired construction is often poor [31]. The bond strength results are significantly impacted by the compatibility of the substrate and repair materials [32]. Figure 7 shows the failure mode. Figure 7 illustrates that the failure modes of S-SF and S-SFL were slant surface failure, but the failure modes of S-Cc and S-CcL were in the repair materials themselves. The test specimens' SC and slant surface were the sites of S-CF and S-CF failure, respectively.

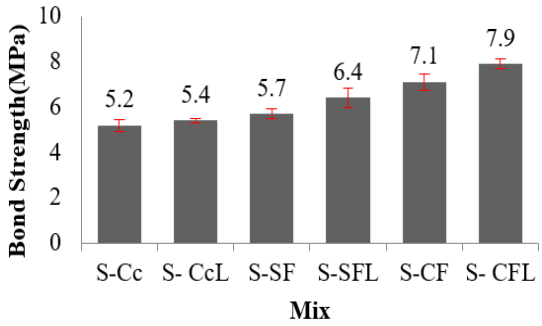


Figure 6. Slant shear bond strength of composite cylinders
Note: *The Bond strength value is the average (Mean) of three specimens (N = 3).

According to the tilt design, not all repair materials will fail. A discrepancy (incompatibility) between the characteristics of the SC and the repair materials could be the cause of this difference from the expected behavior. Pattnaik found three distinct failure modes: Failure of the slant surface indicates a weak connection between the repair material and the SC; failure of the materials (repair material or substrate) shows a weaker material strength than the bond strength at the interface [9]. The main factors that determine bond strength include aggregate interlock, adhesion at the interface, friction, and time-dependent variables. Each of these main elements is dependent upon other factors. Friction and aggregate interlock on the interface are influenced by a number of parameters, including aggregate size, shape, and surface preparation [33].

Table 6. Bond strength for repair geopolymer mortar (GM) mixtures and substrate concrete (SC) at 63 days

Mix	Bond Strength* N (MPa) at 63 Days	Standard Error of the Mean (S.D)	Failure Mode
S-Cc	5.2	0.264	Repair material failure
S-CcL	5.4	0.115	Repair material failure
S-SF	5.7	0.200	Slant surface failure
S-SFL	6.4	0.436	Slant surface failure
S-CF	7.1	0.379	Slant surface failure
S-CFL	7.9	0.208	Substrate concrete failure

Table 7. Flexural strength of specimens for repair geopolymer mortar (GM) mixtures and substrate concrete (SC) at 63 days

Mix	Flexural Strength * (MPa) at 63 Days	Standard Error of the Mean (S.D)	Failure Mode
Ref (Substrate)	5.3	0.208	-
S-Cc	4.3	0.400	center
S-CcL	4.5	0.264	edge
S-SF	4.8	0.153	center
S-SFL	5.1	0.378	edge
S-CF	5.3	0.153	edge
S-CFL	5.8	0.153	center

Note: *The flexural strength value is the average (Mean) of three specimens (N = 3).

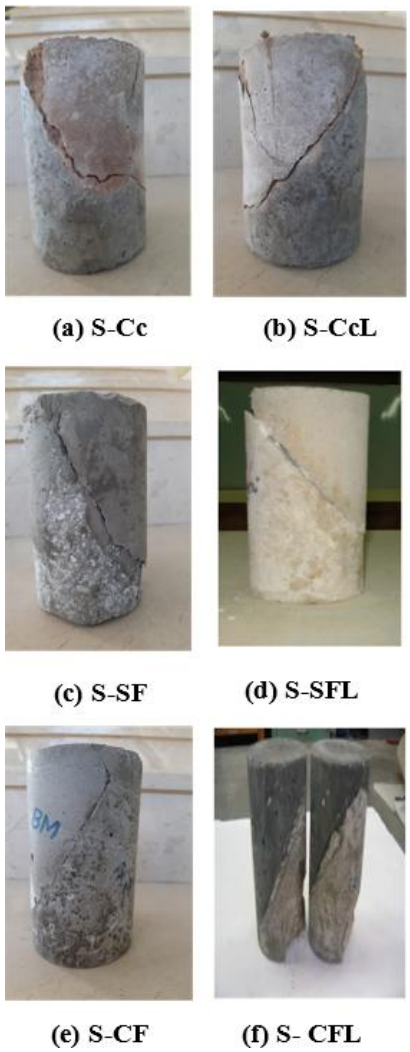


Figure 7. Failure modes of composite section cylinder specimens at the age of 63 days

4.4 Compatibility index of composite specimens for repair of geopolymer mortar mixtures and substrate concrete

According to Pattnaik, the compatibility criteria rely on a prism with a higher total depth value deflecting less than one with a lower total depth value under the same stress in the flexure test. If the repair mechanism fails in bond and there is de-bonding between the substrate and the batched notched area, the overall depth in the composite prism will be decreased [9]. The load deflection curve should also have a less steep slope than the load deflection curve of compatible composite prisms (i.e., without de-bonding). If not, the load will shift to the repair material, and the assembled prism will be considered compatible.

4.5 Third-point loading test (flexural strength)

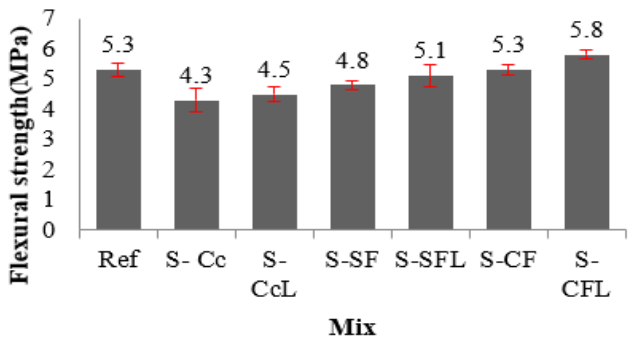


Figure 8. Flexural strength of composite specimens for repair of geopolymer mortar (GM) mixtures and substrate concrete (SC) at 63 days

Figure 8 and Table 7 show the results of flexural strength of composite beam specimens for the repair of GM mixtures, and SC cured at 63 days. The flexural strength of S-CcL was 85% of the flexural strength of reference SC beam specimens, whereas the third-point loading of S-Cc composite specimens was 82% of the flexural strength of reference concrete beam specimens. However, when compared to the reference SC beam specimens, the flexural strength of the S-SF and S-SFL composite beam specimens increased to 91% and 96%, respectively. Comparing S-CF and S-CFL to the reference SC beam specimens, the flexural strengths were 100% and 109%, respectively. The results show that S-CFL was the composite beam specimen that behaved the best; its flexural strength was 109% of that of the reference concrete beam specimens. In general, the composite binder of geopolymer repair mortars S-CF and S-CFL shows better behavior than that of single-source GMs S-Cc, S-CcL, S-SF, and S-SFL. The conjunction of 30%

Cc and 70% SF with 5% SBRL improved the bonding in the matrix of CSH and NASH gel in the GM and played a significant role in the resistance to cracking generated by drying shrinkage; this caused strong bonding between repair mortar and SC that led to an increase in flexural strength [34]. On the other hand, the presence of SBRL in the single and binary mixtures may give a positive indication that the compatibility of repair materials and damaged concrete has been improved. The mix of S-Cc had the highest standard error of the mean, while the mix of S-SF, S-CF, and S-CFL had the lowest standard error of the mean. The standard error of the mean depends on the quality control of the mixes during the experimental work.

4.6 Mode of failure and compatibility results

As shown in Figure 9, the failure mode of the S-Cc was at the centre of the third point loading of the specimen and at the edge of the notch of the S-CcL specimen. This indicates that the SC is incompatible with both of these GMs, whereas the flexural ratio of S-SFL was 0.96. The flexural ratio of S-SF was 0.91, and the failure mode was near the middle of the specimen. This indicates that S-SF and S-SFL are not compatible with the SC. However, when compared to the reference SC beam specimens, the flexural strength of the S-SF and S-SFL composite beam specimens increased to 91% and 96%, respectively. Comparing S-CF and S-CFL to the reference SC beam specimens, the flexural strengths were 100% and 109%, respectively. The results show that S-CFL was the composite beam specimen that behaved the best; its flexural strength was 109% of that of the reference concrete beam specimens.

4.7 Influence of repair geopolymer mortar mixtures on the compressive strength of substrate concrete (crack repair method)

The CS of the average of three composite cube specimens for crack repair of GM mixes, and SC cured at 63 days with S.D, are displayed in Figure 10 and Table 8. While the CS of S-Cc was 96% of the CS of reference specimens, the CS of S-Cc composite cube specimens was 98% of the CS of the reference SC. However, when comparing the S-SF and S-SFL composite cube specimens to the reference SC specimens, the CS rose to 103% and 97%, respectively. Comparing S-CF and S-CFL to the reference SC specimens, the CS were 96% and 101%, respectively.

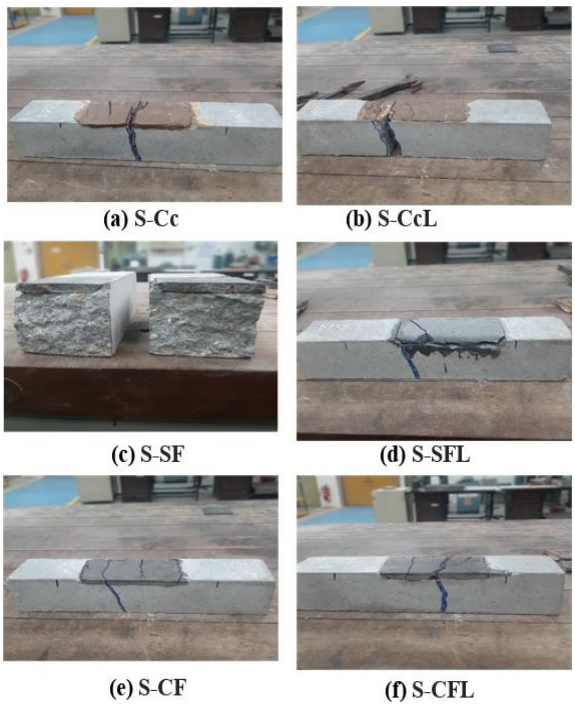


Figure 9. Failure modes of composite section beam specimens at the age of 63 days

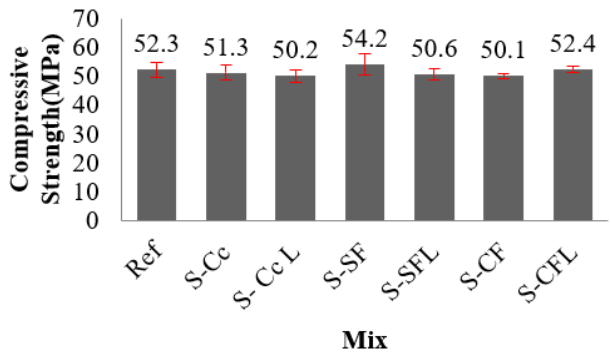


Figure 10. Compressive strength (CS) of composite specimens for repair of geopolymer mortar (GM) mixtures and substrate concrete (SC) at 63 days

Table 8. Compressive strength (CS) for repair geopolymer mortar (GM) mixtures and concrete substrate at 63 days

Mix	Compressive Strength* (MPa) at 63 Days	Standard Error of the Mean (S.D)
Ref (Substrate)	52.3	2.64
S-Cc	51.3	2.63
S- Cc L	50.2	2.12
S-SF	54.2	3.86
S-SFL	50.6	1.99
S-CF	50.1	0.75
S-CFL	52.4	0.96

Note: *The compressive strength (CS) value is the average (Mean) of three specimens (N=3).

According to Frasson et al. [24], the criteria for compatibility of GMs with SC depend on the unit of mass of the specimen and the strength of the loading. It depends on the propagation of cracks during compressive loading. The degree of compatibility of the GMs with the concrete substrate, the results show that the cube with the best behavior was S-CF modified with SBRL, where the CS of S-CFL was 101% of the CS of the reference concrete substrate, and the distribution of cracks following specimen failure under compressive loading all demonstrate the failure modes of composite cubes in Figure 11. The SBRL plays a significant role in improving the bonds at the transition zone between repair materials and SC.

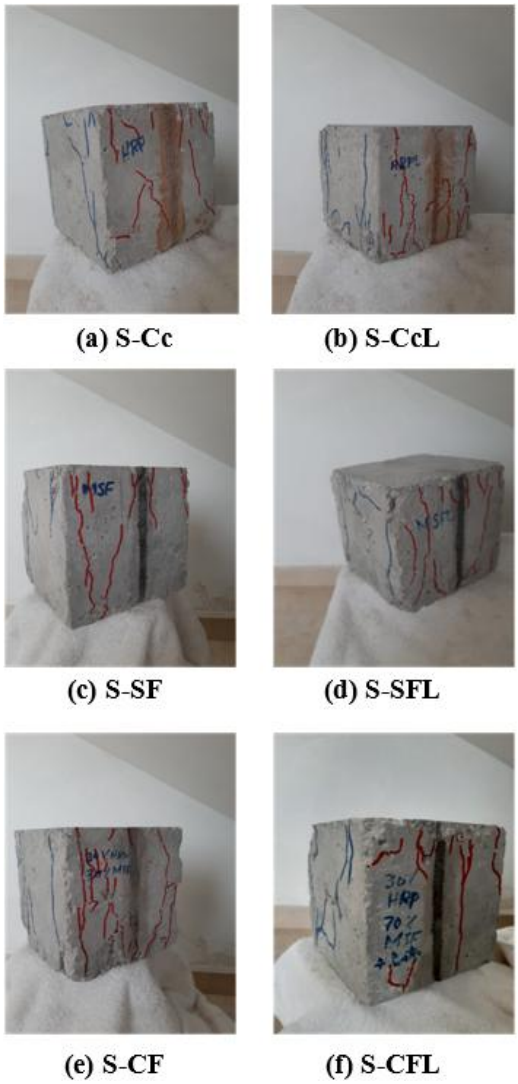


Figure 11. Failure modes of composite section specimens

5. CONCLUSIONS

The higher CS was synthesised with Cc700-based GM. The composite binder of geopolymer repair mortars S-CF and S-CFL shows better behavior in bond strength than that of single-source GMs S-Cc, S-CcL, S-SF with SC failure.

According to the results of the third-point loading test, S-CFL was the composite beam specimen that behaved the best; its flexural strength was 109% that of the reference concrete beam specimens. When compared to reference SC specimens, the CS results of composite specimens for repair GM mixes and SC indicate increases to 96% and 101%, respectively, in S-CF and S-CFL. Additionally, it behaves best when there are cracks in the failure mode.

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NOMENCLATURE

C	clay
Cc	calcined clay
CcL	calcined clay modified by styrene butadiene rubber latex
CF	binary mix of calcined clay and silica fume
CFL	binary mix of calcined clay and silica fume modified by styrene butadiene rubber latex
CS	compressive strength
C-A-S-H	calcium aluminum silicate hydrate
C-S-H	calcium silicate hydrate
GM	geopolymer mortar
N-A-S-H	sodium aluminum silicate hydrate
OPC	ordinary Portland cement
SF	silica fume
SFL	silica fume modified by styrene butadiene rubber latex
SBRL	styrene-butadiene rubber latex
SC	substrate concrete
S-Cc	substrate concrete repaired with calcined clay
S-CcL	substrate concrete repaired with calcined clay modified by styrene butadiene rubber latex
S-SF	substrate concrete repaired with silica fume
S-SFL	substrate concrete repaired with silica fume modified by styrene butadiene rubber latex
S-CF	substrate concrete repaired with binary mix of calcined clay and silica fume
S-CFL	substrate concrete repaired with binary mix of calcined clay and silica fume modified by styrene butadiene rubber latex