

Bond strength analysis of repaired concrete based on polymerization of glycoluril formaldehyde

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ABSTRACT

Repairing old concrete includes the correct choice of material and methodology adopted, which may not affect the quality providing monolithic condition for old and new concrete. This study investigates two different parameters such as the impact as well as optimum usage of new polymer glycoluril formaldehyde as a bonding material. The second one is about to understand the surface preparation for increased bonding strength at the interfacial area of old and new concrete. Five different types of surface textures are used to estimate the bond strength such as plane, lined, waved, grid, and chipped. Glycoluril aids as a bonding material in both old and new concrete, and it is introduced at 0%, 1%, 2%, 3%, and 4% into the cement mixture. When the surface preparation creates a rough surface, it helps in repairing the concrete with the help of polymerization of glycoluril formaldehyde, which promotes the enhancement of bond strength and slant shear. The bond strength of the specimens was measured by slant shear method in compression as well as tension for a period of 1 week and 2 and 4 weeks of new concrete. The results indicated that the highest bond strength was achieved in 3 percentage addition of glycoluril and grid patten substrate preparation.

Keywords: Bond Strength; Slant shear; Glycoluril formaldehyde; Shear stress; Repairing concrete.

INTRODUCTION

Concrete [1] is a flexible and self-adaptable construction material that is used worldwide. A block of concrete is mainly a mixture of fine and coarse aggregated particles blended with a cement fluid and left to harden as time passes by. Different types of binders are mixed with some hydraulic cement to form the concrete mixtures. The Portland cement concrete is formed by binding it together with calcium aluminate cement or with Portland cement. Polymer concrete is formed by using any one polymer as binding material. Nowadays, concrete can withstand any material owing to the bonding agent creating a firm and enduring hardened concrete exterior. Epoxy glue is mainly used as a bonding agent, which consists of two liquids, in which one acts as base and the other as a hardener by mixing at the time of application. The damage that occurs in the construction sites due to natural disasters, soil issues, construction faults, incorrect design, chemical, and mechanical changes overtime is unavoidable in most of the cases. Therefore, the concrete structures built should be regularly monitored closely for any damage to provide immediate

service in case of renovation and repairing. Nowadays, people prefer repairing instead of reconstruction because it gives a timely solution. But the available repairing polymers in market were having demerits like the poor fire and thermal resisting property of epoxy along with a diminishing strength property in the latex [Pothi et al., 2021].

This work aims to involve glycoluril as base material and formaldehyde as curing agent to repair the damaged places in the construction sites instead of replacing them as a whole. The solution offered is mainly a cost-effective and less time-consuming process than renovating the entire damaged structure. Glycoluril formaldehyde (GF) resin is formed by a cross-linkable aminoplast that occurs when glycoluril and formaldehyde react together. The lower crosslink density that exists in GF when cured with functional polymers helps give the concrete structure improved rigidity and toughness. GF sticks together well with the underlying metallic substrate, releases less formaldehyde during the curing process, and is resistant to ultraviolet rays, which makes it more appropriate when used for the exterior surface of the buildings and provides a longer life. The significant factor that corresponds to reducing the concrete repair is the bonding strength that exists between the underlying and overlying concrete (Climaco et al., 2001). Surface preparation is a significant aspect that creates an interface between the old and new concrete (Mirmoghtadaei et al., 2015). The bond strength is mainly improved by factors such as exterior roughness, minor cracks, compaction, and curing. The efficiency of GF in repairing the cracks that occur in the underlying substrate is measured by using two techniques such as slant shear and pull-off method (Júlio et al., 2004, Mirmoghtadaei et al., 2015). The pull-off method is utilized to estimate a material's bond strength and minimize the effect of stress concentration (P. Bocca., 1984). The slant shear is employed to measure the bond strength between the old and new concrete (Diab et al., 2017) when the material is subjected to failure. The pull-off method shall be executed both in situ and in the laboratory, and then, the slant shear method is to be conducted only in the laboratory. This research work adds a new concrete layer to an existing concrete layer by using glycoluril as a bonding medium to the cement layer. The surface is equipped with 1cm cement paste along with 1–4% glycoluril. To add a new concrete layer to an already existing layer, the surface should be coarsened first to help the binding materials stick together. The slant shear test is utilized here to estimate the bond strength of this work. The slant shear test utilizes a cylindrical slab cut into two halves. Every part has a vertical diagonal of 30°. The bond strength of the concrete mainly depends on two main factors:

- The chemical reaction between the repair materials and the underlying surface.
- The concrete surface roughness.

The concrete surface roughness is the most critical parameter that aids in binding the underlying and overlying concrete. A perfect bonding between new and old concrete promotes a sound structure with appropriate binding agent [Pothi et al., 2020]. The concrete should always be built in a manner to increase the shear strength. When the compression strength of the new concrete is higher than the old concrete, it leads to a monolithic rupture. Bond strength also decreases with the period of both the new as well as old concrete added. The only time the bond strength increases is when the new and old concrete mixture has the same mix and the same period (Ji-Tai et al., 2010).

This research article aims to introduce a new polymer-based binding agent named glycoluril formaldehyde (GF). A patent was claimed by Arthur H. Gerber (1986), containing glycoluril in concrete, and no further observable examination is conducted for such kind of polymer. In this study, the adhesion property of old and new concrete using glycoluril-cement paste as binding material with different dosage levels (0%, 1%, 2%, 3%, and 4%) to achieve optimum bonding strength was examined with various types of surface texture (plane, lined, waved, grid, and chipped). The significant factor in improving the bond strength is to use an appropriately prepared surface, which enhances the shear strength of the concrete. Bond stress was evaluated by the slant stress.

LITERATURE REVIEW

In the past few years, many researchers have proposed various methods to strengthen the concrete base. In [6], Mohammadi et al. (2014) discussed the utilization of different chemical elements like silica fume, two kinds of metakaolin, plain cement slurry and bonding slurry [BS], that improved the concrete strength. Metakaolin phase B progresses the bond strength of the concrete. Among them, BS is not suitable to repair the concrete with low performance. Hawa A et al. (2013) [7] used geopolymer mortar such as metakaolin assorted with parawood ash (PWA) and oil palm ash (OPA). However, metakaolin based PWA and OPA contribute less to repairing the concrete. Hence, the research developed new eco-friendly materials for strengthening the concrete repair. The metakaolin geopolymer mortars and carbon fiber reinforced polymers (CFRP) were utilized for improving the bond strength of concrete as mentioned in Vasconcelos et al. 2011 [8]. Here, the bond strength among CFRP and geopolymer mortars is low, and this is not an expected outcome. Moreover, CFRP was not perfect for this level of retrofitting, and geopolymer mortars were costlier when compared to Portland cement.

Kramar S et al. (2016) [9] introduced alkali material for concrete repair. This concrete repair mainly occurs due to building faults, or any other natural disaster caused by the building. Various fly ashes, ground granulated blast furnace slag, and metakaolin are mixed with alkali materials for the concrete repair. Laskar and Talukdar (2017) [10] used an ultra slag based geopolymer to renovate the concrete. However, the performance was low in workability and strength parameter. The sand concrete is utilized as a repair component for concrete in Gadri and Guettala. (2017) [11]. However, the quality and strength of concrete became low. Tayeh et al. (2013) [12] proposed a method called interfacial bond among earlier concrete substrate and ultra-high-performance fiber concrete repair compound (UHPFC). Here, a various-testing method is employed to estimate the strength of concrete, that is, slant shear testing, scanning electron microscopy, and rapid chloride permeability test. Moreover, durability and workability became low in this method. Pacheco et al. (2013) [13] had widely described alkali-activated metakaolin based mortars for the repair of concrete; here, mechanical strength and workability had low.

Self-consolidated concrete (Diab et al., 2017) is used to repair the damaged construction sites by using latex at ten times that of cement rate. The major criteria when repairing the old concrete are illustrated here. The underlying concrete should be strengthened enough by using large grooves to enhance the bonding capacity between the two layers of concrete. Whenever applying new concrete, the mixture should be like that of the old concrete coarseness and aggregate type because the old concrete roughness has a significant effect on inducing bonding. The new concrete mixture compressive strength and bond strength are affected if the strength value mainly differs from the old concrete layer strength. Another factor that determines a bond strength is the test methods (Momayez et al., 2005) used. Some of the tests employed for evaluating the bond strength are pull-off, slant-shear, splitting prism, and bi-surface shear test. Momayez et al. (2005) used a bi-surface shear test to evaluate the weak link that reduces the bonding effect by performing the shear stress test at the interface itself. The results demonstrated that silica fume contact and rough surfaces are the two factors that increase the bond strength. Failure (P. Dybel et al., 2017) mainly occurs in the concrete when bonding the old and new layers by adding a thin layer of an overlay to the existing concrete.

Repairing the old concrete is an interesting topic. It provides a solution to the construction industry, which reduces the cost of demolition and reconstruction. Market available repairing materials aid solutions to the above problems. However, they are having a few faults within, like low performance of Metakaolin, less durability and workability property of UHPFC, diminished mechanical strength, and acid resistance properties of latex. This is an ideal opportunity to consider the new polymer to outdo the shortcomings of available repairing agents.

EXPERIMENTAL INVESTIGATION

Materials Used in this Study

This research is comprised of materials such as Portland Cement, Fine aggregates, GF gel, HCL, M30 grade concrete, and water throughout the repairing process. The fine aggregate used is Zone-I natural river sand, which offers only a few void spaces during bonding and reduces the usage of Portland cement in high quantity. The river sand possesses the following physical specifications: Specific Gravity-2.70, Water retention capacity-2.90, and fitness modulus of 3.36. The cement used here is ordinary Portland cement of grade 43 (IS- 8112), which helps achieve the average compressive strength after 28 days of curing. Glyoxal, Benzil, and Urea are combined to form glycoluril. The glycoluril is synthesized (J.-T. Li et al., 2010) under ultrasound irradiation using potassium hydroxide as a catalyst. Formaldehyde is a material that is formed after the oxidization of methanol. Around 37% of store brought aqueous formaldehyde for the polymerization process, which is a combination of formaldehyde gas in the air. The GF gel is obtained by fusing two materials, that is, glycoluril and formaldehyde together by a polymerization process. Thus, the M30 grade concrete is created.

Measuring the Roughness of the underlying Concrete Surface

To fuse the old and new concrete, the roughness serves as an important factor. To recognize the bond strength of the old concrete before repairing, its surface should be prepared in a rough manner to help the new concrete stick together. The techniques used to create roughness were lined, grid, waved, and chipped by steel knife.

Measuring the Underlying Concrete's Roughness Using the Slant Shear Test

The techniques portrayed above to create roughness are checked with the slant shear method. The specimens are cured at a time interval ranging from 1 week and 2 and 4 weeks. The roughness is considered as an important parameter for conducting the slant shear test. The slant shear test value varies based on the roughness of the underlying surface. If the roughness is high, the slant shear test value also increases. Higher slant shear value indicates a greater bond strength present in between the old and new concrete surfaces. To create a good bond strength, the roughening process should be done deep in the old concrete by using any apparatus. This process helps in the efficient repairing of difficult building structures and historical monuments.

Effect of Adding GF-Gel Paste To The Underlying Concrete Measured by Slant Shear Test

The effect of using GF-gel paste to the underlying concrete to determine the slant shear bond test is reviewed here. GF improves the flexibility and toughness of the underlying concrete. During the curing process, it releases less amount of formaldehyde and provides better adhesion and UV resistant. From these properties, it is clear that the GF gel paste simultaneously increases the bond strength and provides an increased slant shear test result.

EXPERIMENTAL PROCEDURE

Mixture Proportion

To obtain the test results, three sets of cylindrical samples were casted and tested. For the first half-cylinder, old concrete samples are prepared as per ASTM C882, and interface roughness lines, grid, waves, and chipped were created using steel knife in the plastic stage. Then, the specimens are cast, and water cured for 28 days. Afterwards,

the layer above the half-cylinder around 1 cm thick cement glue is mixed with the addition of 1% to 4% glycoluril. Following that, the glycoluril mix is applied on the diagonal surface, and new concrete can be developed.

A concrete mixture is a combination of cement, sand, and concrete aggregate in an appropriate ratio. The strength of concrete depends upon the proportion of mixture in which the binding materials are combined. The specimens were casted for M30 grade concrete. The cement: sand: aggregate ratio in M30 grade cement is 1:0.75:1.5. The sand is applied to half the aggregate volume. Water is added at an approximate level to increase the workability of the concrete. Too much water reduces the strength of the concrete, so here water is added as per the M30 grade concrete standards. The sample specimen created using the mixture proportion described above is illustrated in figure 1.

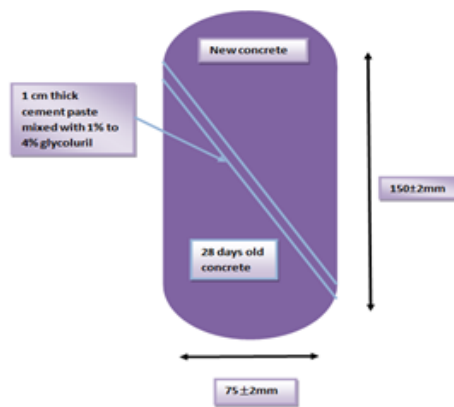


Figure 3. Sample preparation of Specimen created with approximate Mixture Proportion.

Table 1. Concrete mix portion.

Materials	Existing Concrete
Coarse aggregate	850
Water	185
Slump	56
Glycoluril	-
Cement	300
River sand	1105

Bond Strength

The strength of the bond for the repaired concrete was examined during the results evaluated from the analysis of tensile strength as well as the compressive strength. The value equivalent to three tests was examined. The test results of the prepared samples (Pattnaik et al., 2007) were achieved by compressive strength, tensile strength, and

bond strength, while the strength of the bond is considered as the maximum load for further analysis. The specimen of the cylinder was tested at 1 week, 2 weeks, and 4 weeks from the day of casting the entire specimen as well as with polymerized monomer that is aimed to enhance the strength of the concrete composite.

Compressive Strength

The compressive testing machine is used to evaluate the compressive strength of the specimens. The specimen is placed at the center of the pressure plate in the machine. Gradually, the specimen is loaded at the rate of 140Kg/cm²/Minute (68.5kN/sec) till failure as per IS 516.

The subsequent process of preparation on substrate concrete is submitted for studying the effect of surface preparation procedures based on the bond strength of overlay on substrate concrete.

- a) Plane: after the concrete substrates are extracted from the mold, no further action is involved on sample surfaces.
- b) Lines and Waves: to remove cement, metal knife is used to disclose them from an outer surface of specimen. This obtains a mean depth of 2-3mm, and the total length of lines was 133cm approx., and the total length of wave pattern was 136cm approximately (Fig. 2b and c).
- c) Grids: grooves were developed in series along the horizontal as well as vertical portion on the diagonal substrate surface. It has a depth of 2-3 mm as well as a width of 15±1 mm, and a gap of 10±1 mm is created between each other with a total length of 130cm approx. (Fig. 2a).
- d) Chipped: chipped patterns are formed on the plane with a 1cm diameter metal rod at a mean depth of 3 ± 0.5 mm by applying pressure on the interfacial surfaces. Around 25nos±1 of chips are created on the substrate surface (Fig. 2d).

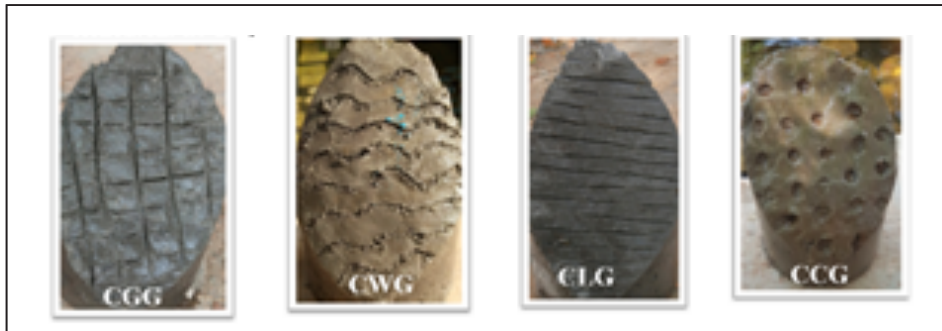


Figure 2. Surface preparation. a) Grid; b) waves; c) lines; d) chipped.

After the surface is roughened using specific tools like metal knife and rod, it is thoroughly cleaned and immersed in water for 28 days for curing process.

The full-cylindrical specimen is formed when the repair concrete is applied on the semicylindrical substrate with a diameter of 75 ± 2 mm as well as 150 ± 4 mm height. The full cylinders are extracted from the mold after 24 hours and cured in water. The slant shear test is loaded with the specimens at the ages of 1 week, 2 weeks, and 4 weeks. The curing time of full cylindrical samples in water is a maximum of one month. The full samples thus developed such as CPG, CLG, CWG, CGG, and CCG are noted in table 2 for the surface preparation methods.

Table 2. Categorization of Specimens.

Methods for Surface Preparation	Code of the specimen
Plane	CPG
Lined	CLG
Waved	CWG
Grid	CGG
Chipped	CCG

RESULTS AND DISCUSSION

Failure modes

The results denoted in Table 3 show the failure modes that are classified into four groups:

- The interface of the substrate, as well as overlay concrete, failure occurs.
- Through the interface, the failure occurs with the occurrence of micro-cracks in the concrete substrate.
- Through the interface, the failure occurs suddenly after the formation of micro-cracks in the overlay concrete and due to debonding in the concrete substrate.
- Through the interface of overlay concrete as well as debonding, failure occurs.

Table 3. Specimens failure modes.

Age of Specimen	CPG	CLG	CWG	CGG	CCG
First week	iv	iv	iv	iii	iv
	iv	iv	iv	iii	iv
	iv	iv	iv	iii	iv
Second week	iv	iii	iii	i	ii
	iv	iii	iii	i	ii
	iv	iii	iii	i	ii
Fourth week	iv	iii	ii	i	ii
	iv	iii	ii	i	ii
	iv	iii	ii	i	ii

The notations used in the above table are described in section 4. The figures explain the bond strength with respect to compression and tension of control specimen, line, wave, grid, and chipped specimens, which consist of different percentages of glycoluril formaldehyde. The advancement of stress at interface results in diminished bond strength of the repaired specimens. This may be of stress development due to differential shrinkage in concrete interface of old and new concrete. Grid pattern showcased a 30% increase in bond strength for a time period of 4th week, which performs well in controlling the interface differential shrinkage. Plane and lined patterns tend to show a lower bond strength when compared to other patterns.

Compression Strength

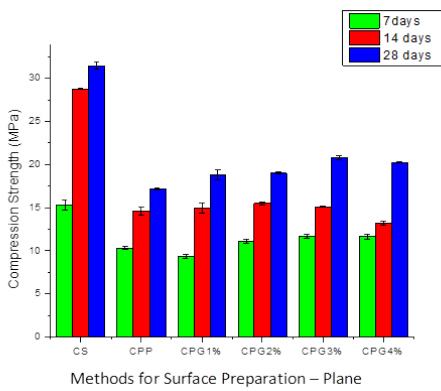


Figure 3. Bond Strength in compression of specimens in that overlay concrete contains plane pattern in interface.

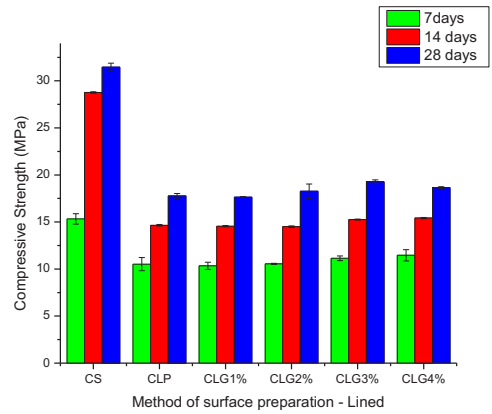


Figure 4. Bond Strength in compression of specimens in that overlay concrete contains lined pattern in interface.

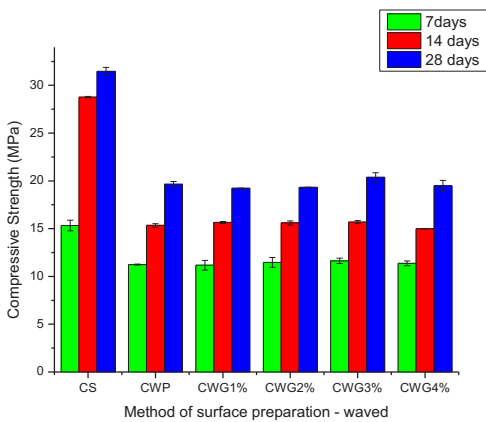


Figure 5. Bond Strength in compression of specimens in that overlay concrete contains waved pattern in interface.

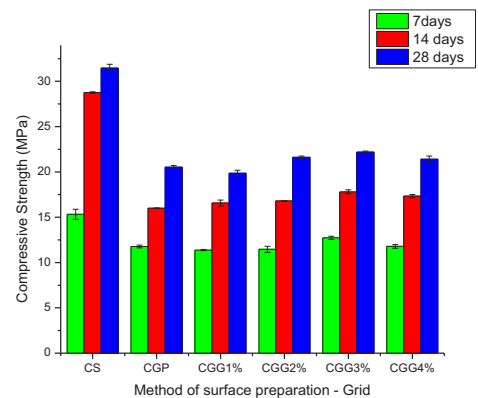


Figure 6. Bond Strength in compression of specimens in that overlay concrete contains grid pattern in interface.

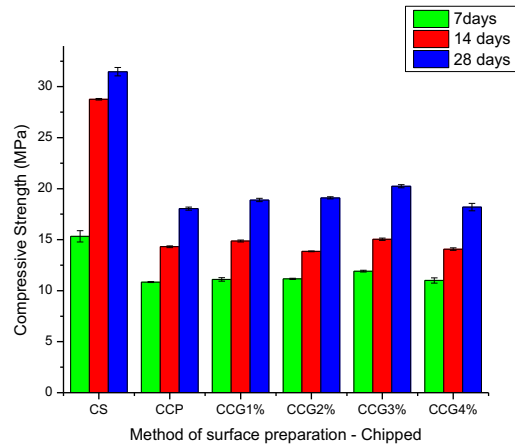


Figure 7. Bond Strength in compression of specimens in that overlay concrete contains chipped pattern in interface.

The figures depict the bond strength of plane, lined, waved, grid, and chipped specimens, which consist of 0%, 1%, 2%, 3%, 4%, and 5% glycoluril formaldehyde. The compressive strength is determined at 35 days, 42 days, and 56 days after the casting of half cylinder (considered as old concrete) as well as at 7 days, 14 days, and 28 days for new concrete. Compared with the full cylinder, the compression strength of slant specimen is minimum since the applied compressive force on the slant surface may act as principle tensile force. Due to this tensile force, the slant specimens do not contribute to the full cylinder.

Most of the cylinder failed with the slant surface, but the surface roughness of the specimen improved the strength property. The result shows that the addition of glycoluril as bonding agent interface increased the strength compared with the cement paste. Due to the polymeric dispersion in the glycoluril, the compressive strength of the specimen with glycoluril is noted to increase. This polymeric dispersion paves the way for sealing the pores and increasing the bond strength. Early strength development is also observed while incorporating cement paste as interface bonding material. Particularly, 3% addition of glycoluril showed considerable rise in result. The surface roughness also plays a key role in the strength enhancement. In this study, five different surface textures are studied: plane, waved, lined, grid, and chipped surface. In this surface preparation, increasing the bond strength but comparing all textures, grid surface provides good result. Thus, 3% addition of glycoluril in the cement paste as a bonding agent with surface roughness in grid pattern is recommended in comparison with the other patterns.

Tensile Strength

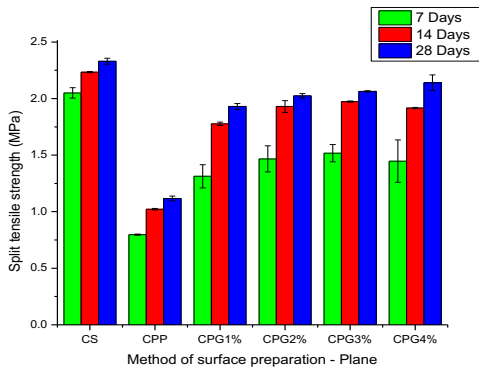


Figure 8. Bond Strength in tension of specimens in that overlay concrete contains plane pattern in interface.

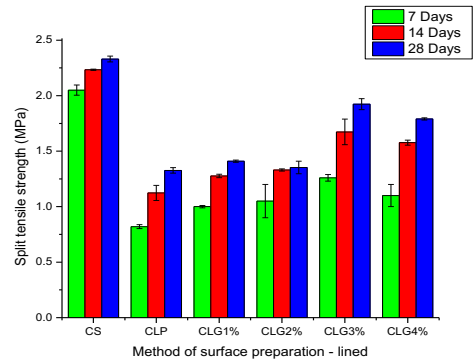


Figure 9. Bond Strength in tension of specimens in that overlay concrete contains lined pattern in interface.

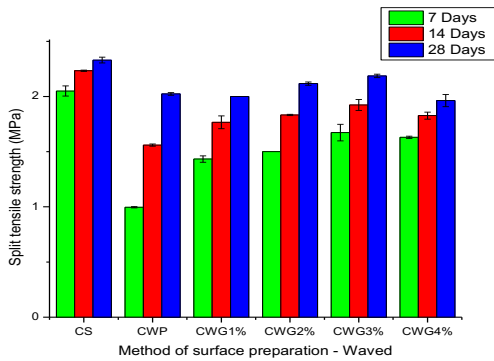


Figure 10. Bond Strength in tension of specimens in that overlay concrete contains waved pattern in interface.

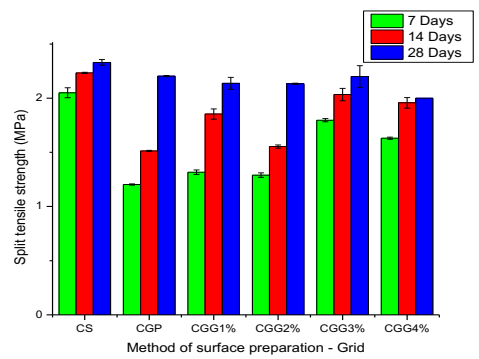


Figure 11. Bond Strength in tension of specimens in that overlay concrete contains grid pattern in interface.

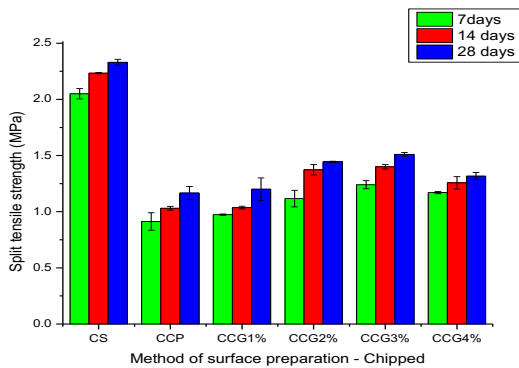


Figure 12. Bond Strength in tension of specimens in that overlay concrete contains chipped pattern in interface.

The bond strength in tension is valued with split tensile test. An average value corresponding to the 3 samples is tested for each type of interfacial concrete surface and presented in the above graphs [Fig. 8 to Fig. 12]. In general, the bond strength of the concrete interface is improved by increasing the glycoluril content in cement paste; when the same is extended up to 3%, the bond strength is observed to decline. This is attributed to the excess polymer in cement paste that initiates hydration of the cement paste. This phenomenon is also observed by Ma et al. (2013) and Retno et al. (2014).

The surface roughness also enhanced the bond strength particularly in the specimens with grid pattern in the interfacial area. The assessment of the bond strength in tension zone proved that the increase of surface roughness and increased percentage of glycoluril content improved the bond strength. While comparing the surface roughness condition, we noticed that the grid pattern in concrete interface developed a significant rise in bond strength, whereas the line patterned specimens showcased poor bond strength. The results show that 3% addition of glycoluril with grid pattern exhibits a higher tensile strength among all other specimens for all the ages of concrete. Beyond the 3% glycoluril addition, the tensile strength of the specimens similar to that of the compression strength is lowered.

Water Absorption and Sorptivity Test

Water absorption and sorptivity test were also conducted after four weeks of curing period. Initially, the specimens were oven-dried at 105°C for 24 hours, and constant weight of all the specimens was noted before testing. For sorptivity test, except the bottom, all the other three sides are coated with nonabsorbent resin. The results are clear that these two tests are not appropriate to find the properties of pores in the concrete specimens developed in this study since the weight of the specimens remains the same even after the absorption and capillary rise of water when compared with the control specimen. A small amount of polymer in the interfacial layer may not contribute to the density.

Scanning Electron Microscope

Since the water absorption and sorptivity test were found to be inappropriate to validate the pores and density parameters, scanning electron microscope (SEM) imaging test is conducted on the developed specimens. The microstructural SEM images (Figs. 13, 14) are presented for the 3% addition of glycoluril with cement paste that is used in the interfacial zone. The images were obtained for two different dimensions such as 30 μ m and 3 μ m with magnitude of 1000x and 5000x, respectively. Addition of small amount of glycoluril in the binder resulted in the formation of denser microstructure with minimal air voids. No microcracks were detected in the SEM images owing to the presence of polymer that bonds well with hydrated cement enhancing the bonding cohesion and cement matrix strength. At higher magnification, few pores were noticed, whereas the major portion is observed to be closed packed owing to the presence of the polymer that adheres the cement hydrates. Chemical reaction between the NH group of reactive polymer and calcium hydroxide provides good bonding and better density for the concrete specimens.

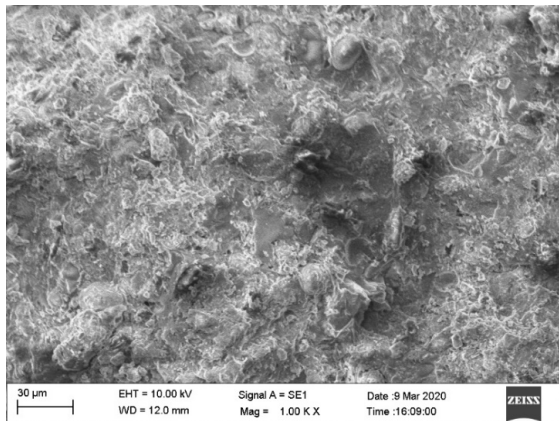


Figure 13. SEM image of 3% glycoluril addition at 30µm.

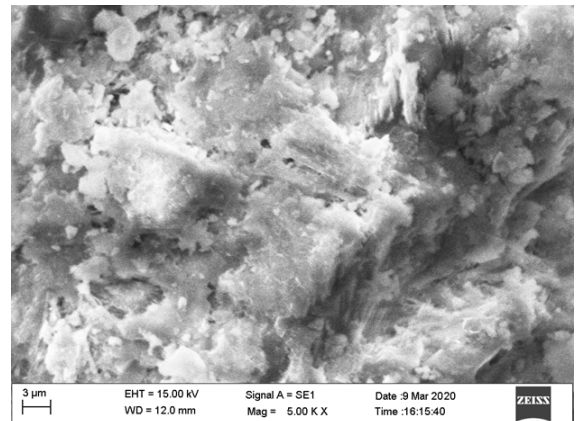


Figure 14. SEM image of 3% glycoluril addition at 3µm.

SUMMARY AND CONCLUSION

Based on the experimental analysis, the bond strength is evaluated at the interfacial zone, and the following conclusions were drawn:

1. The present paper introduces a novel approach for repairing old concrete using polymerization of glycoluril formaldehyde.
2. The major parameter considered for determining the bond strength between the old and new concrete together is the surface preparation and roughness, which also acts as an interfacial zone.
3. The slant shear test is conducted to measure the roughness of the underlying concrete surface. It is considered as one of the significant parameters in this study. The test is also carried out in a simplified approach. The slant shear strength is conducted to measure the bond strength of the repaired concrete in this proposed method, which tends to be slightly higher due to increased roughness.
4. A thick layer of the adhesive mixture is developed by combining cement paste and GF gel. This mixture is used in different proportions for about 1 cm thick between the two concrete layers to reconstruct the damaged old structures.
5. The overall performance is evaluated by measuring the compression strength and tensile strength of the concrete. From the results, it is evident that the strength of the new concrete is slightly lower than the old concrete, which prevents the monolithic rupture. But the 3 % addition of glycoluril in the concrete interface provides considerable bond strength against the loading.
6. Five techniques, that is, plane, lined, waved, grid, and chipped patterns, are used in this paper to measure the bond strength between the underlying and overlying substrate. Among these concrete specimens, the grid pattern yields relatively higher performance in repairing the older concrete. The combination of 3% glycoluril formaldehyde with grid layer at interface resulted in improved resistance of the interfacial concrete surface failure and provided greater bond strength.
7. Hence, the proposed method is effective in rebuilding the old construction sites.

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