

Evaluation of Properties and Feasibility of Non-Metallic Geopolymer Coating for Corrosion Protection of Rebars

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ABSTRACT

RCC is the basis of major high rise infra of country and the world, but the major loophole working with RCC is corrosion of embedded steel. This corrosion not only causes premature deterioration of the structure, but also makes the structure unserviceable or fragile and shabby. Geopolymer is an inorganic polymer, an alkali-activated binder which has gained worldwide interest and its high anticorrosion property made it a novel coating material. The reaction of solid aluminosilicate material with highly concentrated aqueous alkali hydroxide or silicate solution to produce a synthetic alkali aluminosilicate material generically called “geopolymer” and can be compared in performance with the traditional cementitious binders in a range of applications, but with the added advantage of significantly reduced greenhouse emissions. The geopolymer solution can be tailored by correct mix and processing to optimise properties such as flexibility, adhesion and to offer excellent corrosion resistance properties with reduced cost for given coating applications.

Therefore, by considering the advantages offered by geopolymer binder such as greener material, good corrosion and alkali, acid resistance, fire resistance and also excellent adhesion to steel substrate with high electrical insulating effects, the geopolymer binder is chosen with different kind of aluminosilicate materials.

Twenty different geopolymer based compositions using fly ash, OPC, Microsilica, Rice husk ash, Clay, China Clay, Kaolin, Ferrosilicon Powder, Vanadium Pentoxide, Silica fume and Fe₂O₃ as functional pigments and fillers were formulated and brush able coating materials were synthesised. A combination of Binder + Fly ash + Clay + Iron oxide yellow and Binder + Fly ash + Rice husk ash + Iron oxide yellow individually have passed all the examinations as per the experimental conditions adopted in the present study and may be very well utilized for preventing or decelerating the corrosion rate of steel rebars in concrete.

1. INTRODUCTION

Steel corrosion in concrete includes a complicated chain of events, the proportions of which might change depending on the exposure to the environment and the properties of the material. However, the entire procedure might be condensed into a number of universal responses. The following is the chemical processes involved in the deterioration of steel within concrete:

In most cases, iron (Fe) atoms enter the solution at the anodic site as positively charged (Fe²⁺) hydrated ions

& freed e⁻s rush to the cathods and get absorbed by dissolved oxygen.

Hydroxide (OH⁻) is a common component of solution in high-pH environments like concrete. Iron may react with hydroxyl ions and produce ferrous hydroxide (Fe(OH)₂) at steel surface. This is referred to as the anodic reaction in electrochemistry. Dissolved oxygen (O₂) combines with water (H₂O) and electrons produced by the anodic reaction to form hydroxide ions simultaneously at a different place on the steel

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surface (OH⁻). The whole process is a cathodic reaction. A corrosion cell is formed by the combination of the anodic and cathodic processes, and the reactions take place concurrently. Fe (OH)₂ continues to react with oxygen and water to produce insoluble corrosion products, notably hydrated iron oxide compounds in solution, which build up in the interfacial region and small pore spaces surrounding the steel. The iron oxides include magnetite, ferric oxide (Fe₂O₃), reddish-brown rust and Fe₃O₄, black rust. This is a condensed explanation. The concrete pore solution contains a large number of additional ions, and the steel's precise composition varies. Since changes in the pH, oxygen supply, and moisture level of concrete may also affect the precise products. The following generalised equation for corrosion products was provided in the literature (Liu & Weyers 1998). The bar spontaneously develops a thin "passive" layer of oxidised ferrous (Fe²⁺) and ferric (Fe³⁺) molecules shortly after being set in freshly-poured concrete. The layer is a layered film, with ferric oxide acting as an insulating layer atop conductive magnetite at the steel surface. The growth of the passive layer (a corrosion process in and of itself) proceeds at an ever-decreasing rate in the high-pH (13) environment and in the absence of aggressive ions, until the rate of iron dissolution becomes negligible. The passive layer usually shields the reinforcement against spontaneous corrosion in the damp concrete environment once it has been created (Bentur et al. 1997).

2. Literature Review's

Kumud Deshmukh et al 2021 looked at geopolymeric materials based on fly ash with various silicate: alkali ratios as covering materials on mild steel plates. According to the study, the majority of the fly ash peak patterns in the processed materials' XRD results can be attributed to the quartz and mullite phases of the fly ash, which did not transition into an aluminium silicate gel as a result of the geopolymerization event. However, the appearance of a novel sodium aluminium silicate phase (NaAl₃Si₃O₁₁), as well as an amorphous phase, in the coating material compositions suggested that an amorphous aluminosilicate gel had formed as a result of a geopolymerization reaction. The newly created coating material exhibits promising mechanical, heat, corrosion, and fire-resistant qualities.

Alehyen et al. 2017 a concrete covering made of fly ash was researched by analysed using equipment like XRD, FTIR, Raman, DSC, and SEM. The geopolymer has an amorphous character with a minimal crystalline phase, according to the results of the XRD examination. The spectral band related to Si-O and Al-O, as well as their displacement towards lower

values, were identified through the examination of FTIR Spectra. This change was explained as the result of Al penetrating the Si-O-Si skeleton's original structure, as was seen similarly in zeolites. The geopolymer specimens' microstructure encouraged the development of a heterogeneous matrix, which is made up of a dense continuous gel-like structure with microscopic pores and fissures. DSC calorimetry was used to evaluate the thermal stability of a geopolymer made from fly ash, and the results indicated that the geopolymer has excellent thermal characteristics. Zetametry was used to investigate the chemical stability, and the great stability of the geopolymer suspensions was suggested by the huge measured negative value of the zeta potential. Additionally, research into water absorption capabilities revealed that geopolymer paste absorbed less water than standard Portland cement control samples.

Noor Fifinatasha Shahedan et al. 2016 applied geopolymer coatings on glass fiber-reinforced epoxy (GRE) pipe utilising kaolin, white clay, and silica sand as source materials and sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) as an alkaline solution. The interfacial layer and microstructure between the geopolymer coating and GRE pipe are established as a result, and this has a substantial impact on the mechanical properties of the geopolymer coating. However, the microstructure and properties of the geopolymer covering varied depending on the source materials.

Farah Farhana Zainal et al. 2016 revealed that the composition of the geopolymer had a significant impact on the coatings' adhesive strength. The amount of water in the formulation determines how easily geopolymer can be applied to metal surfaces and the thickness that results. The optimised coating compositions' thermal and microstructural evolution demonstrate its highly encouraging fire-resistant qualities. When implanted in a Class F fly ash geopolymer, steel rods with and without the glassy enamel covering rich in Al, Si, and Ca were put to the test for bond strength. Based on push-out test specimens, it was discovered that applying a reactive enamel coating to reinforcement increased bond strengths by almost 2.5 times. Additionally, it was discovered to provide a more gradual transition in microstructure and chemistry between the steel reinforcement and the geopolymeric matrix, as well as to reduce porosity at the interface. A Class F fly ash-based geopolymer with alkaline activators was also tested utilising Open Circuit Potential (OCP) testing as a covering material.

According to the Pourbaix diagram for OCP testing, the samples were in the region of passivity. OCP had a

potential ranging from 0.015 V at the lowest end to 0.133 V at the highest. In addition, the adhesion test on day 14 produced the maximum result of 2.0MPa. It was because, as shown by morphological study, the structure of the geopolymer paste becomes more compact, denser, and capable of better crystallisation from days 3 through 14.

Irfan Khan et al. 2014 in their paper concluded that a Class F- fly ash-based sodium silicate free geopolymer with Na/Al=1 was able to attain a maximum adhesion strength of 3.8 MPa. It was discovered that geopolymers barely slightly changed in terms of adhesion strength after the first three days, when they reached their maximum strength.

Kelly Cristiane Gomes et al 2013 carried out study of the alkali-activated clay-based waste's binding capability in steel-bonded plates, other alkali-activated aluminosilicate materials performed better than the traditional geopolymer precursor metakaolin (MK) in terms of adhesive capabilities. A relative thermal efficiency was achieved when two separate mineral- and one industrial waste-based geopolymers were utilised as adhesive in steel plates. Geopolymers performed better than an epoxy-based glue in terms of load retention at temperatures as high as 400°C. All other adhesives demonstrated a load decrement with temperature, however the metakaolinite-geopolymer system was not significantly impacted by an increase in temperature up to 400°C. Similar trends appear to apply to the influence of the Si:Al ratio on the adhesive qualities of geopolymers as they do for bulk compressive strength. The crack propagation load in all systems increases with the precursor's Si:Al ratio. However, it appears that the load on all systems decreases more the higher the iron oxide content. Therefore, caution must be exercised in assessing the possibility of gas-generating reactions, such as those caused by specific hydrated iron-rich phases that may exist in some mineral and industrial wastes. The mechanical effectiveness of the steel plates' bond may be decreased as a result of this reaction

3. MATERIAL USED ALKALINE LIQUIDS AND SOURCE MATERIALS

In the present experimental work, the source materials and the alkaline liquid are the two basic components of geopolymers. For geopolymers based on alumino-silicate, the source materials should be abundant in silicon (Si) and aluminium (Al). These could be natural minerals with Si, Al, and oxygen (O) in their empirical formula, like kaolinite, clays, micas, spinel, etc (Davidovits 1988c). As an alternative, filler materials made from byproducts such fly ash, microsilica, rice husk ash, clay, china clay, kaolin,

ferrosilicon powder, and silica fume were employed. The choice of the raw ingredients used to create geopolymers depends on a number of variables, including cost, application type, availability of reactive materials, and unique end-user requirements. The soluble alkali metals that are used to make the alkaline liquids are typically sodium- or potassium-based.

Twenty different combinations of geopolymer anticorrosive coatings for steel reinforcement in concrete structures were developed using by-products and mineral ingredients. But you can use any other fine material as a precursor for a binder if it comprises sizable amounts of silicon and/or aluminium retained in an amorphous phase. These materials include rice husk ash and calcined clays (Wang et al. 2005, Liew et al. 2011). (Kim et al. 2014). The main prerequisites for geopolymerization are materials high in silicon (such as fly ash or slag) and materials rich in aluminium (such as kaolin clay) (Khale et al. 2007). Subsequent headings further, provide specifics regarding the sources of the raw ingredients and their chemical make-up.

Alkaline Liquid

The alkaline liquid was decided upon as being a mixture of sodium silicate solution and sodium hydroxide solution. Because sodium-based solutions were less expensive than potassium-based ones, they were chosen. The sodium hydroxide (NaOH) in flakes or pellets form with 97%–98% purity and the sodium silicate solution (Na₂O= 13.7%, SiO₂=29.4%, and water=55.9% by mass) were bought from a local supplier.

In order to make the sodium hydroxide (NaOH) solution, the pellets were dissolved in water. The mass of NaOH solids in a solution varied according to the solution's molar, or M, concentration. For instance, a 0.5M solution of NaOH required $0.5 \times 40 = 20$ grammes of solid NaOH (in the form of flakes or pellets) per litre of water, where 40 g is the molecular weight of NaOH. The ratio of NaOH and Na₂SiO₃ in the final geopolymer solution (binder solution) was 1:3.

Ordinary portland cement

Ordinary Portland Cement (OPC) used for this study is conforming to Indian Standard IS 12269-1987 of grade 53. In the present experimental work, ordinary Portland cement is purchased from a local supplier in bulk was used as the reactive material.

Fly ash

Class F fly ash from the Khedar Thermal Power Plant was used as the reactive material in the current experiment. The main components of these earth

elements in the micron range are silica, alumina, and iron. The nearly completely spherical shape of fly ash particles allows them to flow and integrate freely in mixes. The nature of this fly ash is pozzolanic.

Micro silica

An amorphous (non-crystalline) polymorph of silicon dioxide is called micro silica. It is an ultrafine powder with spherical particles and an average particle diameter of 150 nm that is gathered as a waste product from the manufacturing of silicon and ferrosilicon alloys. It principally comprises of exceedingly small, smooth, spherical silicon oxide particles with a very large surface area. The average cement particle is 100 times larger than micro-silica particles. Amorphous Reactive Silica, Pozzolanic, which interacts with Ca(OH)₂, and LOI, which is less than 4%, are some of the chemical components of microsilica. Minimum SiO₂ content is 85% (usually 90+%). The "Filler effect," which reduces pore diameters and Ca(OH)₂ content, is one of microsilica's benefits in concrete. Micro-silica has evolved into a flexible mineral admixture for a variety of applications, including coating formulation, as a result of its special chemical and physical characteristics.

Umesh Sharma et al. (2014) suggested one such use in which the decreased permeability of micro-silica protects against the infiltration of chloride ions, lengthening the time it takes for the chloride ions to reach the steel bar and begin corrosion. Additionally, compared to OPC concrete, micro-silica concrete has substantially higher electrical resistance, which reduces the rate of corrosion. The coating's endurance is increased by the addition of microsilica.

Rice husk ash

Husk, a by-product of the rice milling process, is utilised as fuel in the rice mills to provide steam for the parboiling process. About 75% of the husk's volatile organic compounds are organic, with the remaining 25% Rice Husk Ash, which is produced when 25% of the weight is reduced to ash during the burning process (RHA). Amorphous silica, which is finer than cement and has very small particle sizes of 25 microns, is also included in this RHA to fill the spaces left by the cement in the aggregate, which determines the strength and density of the concrete. RHA was acquired from nearby rice mills and fired in a furnace to 900°C for four hours.

China clay

Hydrated Aluminum Silicates, such as China Clay, are frequently employed in polymer applications and help to increase chemical resistance, electrical characteristics, and water absorption. It decreases the likelihood of completed products cracking, boosts shock resistance, and enhances surface quality. Micro

China Clay is frequently used in the production of paints and oil-bound distemper. It can be manufactured as a white powder that is specified (partially) based on its brightness and whiteness and is chemically inert. It is perfect for a variety of ceramic, filling, and coating applications where the completed product's appearance is crucial (Jepson 1984). When used as a surface coating pigment on premium glossy paper, which may have up to 30% of the mineral, it is especially useful. China clay was procured from local hardware shop.

Kaolin

One kind of clay is kaolin. Its whiteness and flexibility make it ideally suited for usage in coatings as a filler, extender, raw material for ceramics, and pigment. It is also a crucial raw ingredient for the cement, fibre glass, refractories, and catalyst sectors. It is a special industrial mineral that gives excellent covering when used as a pigment or extender in coated films and filling applications. It is chemically inert over a broad pH range. It also has a low conductivity for heat and electricity and is soft and non-abrasive. The coating of paper to conceal the pulp strands and the creation of premium ceramic items are the two main uses of kaolin. Kaolin was purchased from chemical suppliers for the coating compositions.

Ferrosilicon powder

Ferrosilicon is used as an auxiliary material in the steel and ferrous industries. Additionally, the primary consumers of silicon metal are the chemical and aluminium industries. There are two standard grades of ferrosilicon, one grade with approximately 50 percent silicon and the other contains 75 percent silicon by weight. The purity of silicon metal generally ranges from 96 to 99 percent.

Vanadium pentoxide

Vanadium pentoxide (Vanadia) is an inorganic compound with the molecular formula of V₂O₅. It is generally a brown/yellow solid, although when freshly precipitated from aqueous solution. Vanadium is widely distributed and relatively abundant in the crust of the earth, although reserves of ore-grade vanadium that can be mined are scarce. The majority of vanadium is produced as a by-product or co-product of the iron, titanium, phosphorus, and uranium ore processing industry. The most frequent way to extract vanadium from these ores is as pentoxide, but it can also be done with sodium and ammonium vanadates. We bought vanadium pentoxide from regional chemical distributors.

Silica fume

Silica fume is an ultrafine airborne substance made up of spherical particles with an average diameter of around 0.1 μm and a diameter of less than 1 μm. This

makes it approximately 100 times smaller than the normal cement particle. The metal from which silica fume is formed determines its unit weight or bulk

density. Typically, its unit weight ranges from 130 to 430 kg/m³. Typically, silica fume has a specific gravity between 2.20 and 3

Nomenclature for different coating systems

Sl. No.	Coating Code	Materials used
1	GPR	Binder(25ml) + Fly ash(10g) + Iron oxide Red (2g) +Silica fume(0.2g)
2	GP1	Binder(30ml) + Fly ash (10g) + Iron oxide yellow (2g) +Silica fume(0.2g)
3	GP2	Binder (30ml) + Micro silica (10g) + Iron oxideyellow(2g) + Silica fume(0.2g)
4	GP3	Binder(30ml) + Fly ash(5g) + Micro silica(5g) + Ironoxide yellow(2g) + Silica fume(0.2g)
5	GP4	Binder(50ml) + OPC (10g) + Iron oxide yellow+ Silicafume(0.2g)
6	GP5	Binder (40ml) + OPC(5g) + Fly ash(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
7	GP6	Binder(40ml) + OPC(5g) + Micro silica(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
8	GP7	Binder (40ml) + OPC (3g) + Fly ash(4g) + Micro silica (3g) + Iron oxide yellow(2g) + Silica fume(0.2g)
9	GP8	Binder(40ml) + OPC(5g) + Kaolin(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
10	GP9	Binder(50ml) + Fly ash (5g) + Kaolin(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
11	GP10	Binder (40ml) + Fly ash(5g) + Clay(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
12	GP11	Binder(40ml) + Fly ash (5g) + China clay(5g) +Iron oxideyellow(2g) + Silica fume(0.2g)
13	GP12	Binder(40ml) + Fly ash(5g) + Rice hush ash(5g) + Ironoxide yellow(2g) + Silica fume(0.2g)
14	GP13	Binder(40ml) + OPC (5g)+ Clay(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
15	GP14	Binder (40ml) + OPC(5g) + China Clay(5g) + Iron oxideyellow(2g) + Silica fume(0.2g)
16	GP15	Binder (40ml) + OPC(5g) + Rice husk ash (5g) + Ironoxide yellow(2g) + Silica fume(0.2g)
17	GP16	Binder(40ml) +Fly ash(5g) + Ferrosilicon powder(5g) + Ironoxide yellow(2g) + Silica fume(0.2g)
18	GP17	Binder(40ml) + OPC(5g) + Ferrosilicon powder(5g) + Ironoxide yellow+ Silica fume(0.2g)
19	GP18	Binder(40ml) + OPC(9g) + Vanadium Pentoxide (V ₂ O ₅) (1g) + Iron oxide yellow(2g) + Silica fume(0.2g)
20	GP19	Binder (40ml) + Fly ash(9g) + Vanadium Pentoxide (V ₂ O ₅)(1g) + Iron oxide yellow(2g) + Silica fume(0.2g)

4. RESULTS & DISCUSSIONS

Adhesion Test

Adhesion is an interfacial phenomenon which occurs when two surfaces approach each other to form an interface by physical, chemical or mechanical anchoring of the coating with substrate metal. Excellent adhesion of coating with the substrate is essential for anticorrosive coatings. Inadequate adhesion will promote coating failure by exposing the bare metal to the aggressive environment, causing corrosion.

Tensometer has been used to carry out a coating adhesion test. In which a certain force is applied to the coated surface. The instrument's digital display showed that the load at failure had been noted. Each coating's consequential stress value was estimated at failure. The predicted outcomes are shown in Table . Since the coating is applied to pockmarked surfaces, many coatings have produced reduced adhesive stress since there is less abrasion on the metal substrate. Particle coating strength was determined to be 8.12 N/mm² for G13 and 8.128 N/mm² for G16, respectively. The maximum value, however, of 24.319 N/mm², was attained for G12. For coatings G9 through G12, good adhesive strength was often attained. The coating's geopolymerization with clay material that has included 123 has helped it produce a strong formulation during geopolymerization. Therefore, the formulation of silate by aluminium silicate materials with the geopolymer binder was given credit for the high adhesive strength.

The mechanical adhesion with large surface area having minute pits and ridges provide best anchoring for the coating along with chemical bonds formed by OH ions of the coating with metal substrate. Therefore, the coatings GP9 to GP12 provided very high adhesive strength of 4N/mm^2 (Sorensen *et al.* 2009).

Flexibility Test (ASTM D522)

The flexibility of coated plate was determined by a mechanical test on a mandrel, in which a coated plate was rolled to a mechanical shape with the assistance of a handle and cone. The coatings were deemed to be "Passed (P)" if there was no evidence of a crack on the commercial network after the test. If flaws are discovered in the coating, the building was marked as "Failed (F)". The findings of this test, which was conducted on all twenty specimens, are listed in Table . The G7, G13, and G16 coatings failed this test of contractual flexibility. All three of these coatings are composed of silica rich coatings, and only Al_2O_3 is added. A hard geopolymer form was made possible by the composition's richness in silica, which gave rise to the composition. Therefore, these three coatings are failed in the flexibility test.

In addition of the rigid silicate formation the added pigments such as microsilica in GP7 and rice husk ash in GP13 and GP16 and well micronized and excess quantity with the geopolymer binder has reduced the elasticity and flexibility property and therefore it has to be optimised to avoid failure. However, all other coatings the ratio of binder to pigments are sufficient enough for extensibility without causing cracks in this test.

Impact Test

Impact tests have been conducted on coated MS plates in accordance with STM D2794 and on coated rods in accordance with STM D14. After the impact, the impact of the steel ball on the coated plate surfboard will leave a mark in terms of opinions. The imprinted/impacted plate was examined on the reverse side of the imprint with the use of magnifying glass to look for any cracks, fractures, or delamination. Both the plate and the coated rod that showed no flaws were rated as "Passed(P)" while the flaw-filled coatings were marked as "Failed(F)". The outcomes are listed in Table .

In this study the coatings GP8, GP13 and GP16 were failed both in plate and rod impact test. These combinations with OPC, Rice husk ash and microsilica are the reasons for failure. The hydration of OPC and the pozzolanic activity of RHA and fly ash may be the reason when comes in contact with water in the binder solution, before cross linking starts by geopolymer solution. Thin failure can also be attributed that the formation of double elasto-plastic rigidity. One by hydration and pozzolanic activity of fly ash and RHA, and the other rigidity by the geopolymerisation with alumino silicate materials. These two different elasto-plastic rigidities on single impact load leads to differential impact and that causes failure of coating by the formation of cracks and delamination of the coating material from the substrate. Except these three coatings all other coatings were passed in this test.

Hardness Test (ASTM D 3363)

The coatings industry has employed pencil hardness measurements for many years to assess the toughness of clear and pigmented organic coating films. This test method has also been used to ascertain the cure for various coatings, particularly when forced dried with heat. This method was applied to the geopolymer coating in the recent study. A coated panel is set up on a solid horizontal surface. The pencil is firmly held against the film at a 45° angle (point away from the operator) and is pushed away from the operator in a 6.5-mm (1/4-in.) stroke. The procedure began with the hardest pencil and progressed all the way down to the hardest level of difficulty. All the twenty coatings are subjected to the pencil hardness test and are tested with 12 pencils ranging from 6B to 6H. The coated surfaces were scratched by these pencils led which was made to the shape of chisel and scribed with an angle of 45° with horizontal. All the coatings are passed in this test without any visible scratch. This indicates unlike organic coatings the prepared geopolymer inorganic coatings were found very hard. The results are summarized in Table . represents the performance of the twenty geopolymer formulations in flexibility, impact and hardness test.

The reason for non-failure of the coating is simple; the coatings are sufficiently hard enough by rigid film formation, secondly, the coating possesses enough thickness thirdly the adhesion of coatings with the substrate metal is very strong.

Table Results of Mechanical Properties of Coatings

Designation of Coating	Coating Thickness (urn)	Adhesion Test (by Tensometer)		Flexibility Test (ASTMD-522)	Impact Test		Hardness Test (6Bto 6H) (ASTM D 3363)
		Load at Failure N	Stress at Failure N/mm ²		On coated plates ASTM D2794	On coated rods ASTM D14	
GPR	220	6.785	13.819	P	P	P	P
GP1	226	7.102	14.464	P	P	P	P
GP2	210	7.631	15.541	P	P	P	P
GP3	223	6.992	14.240	P	P	P	P
GP4	219	6.846	13.943	P	P	P	P
GP5	210	6.911	14.075	P	P	P	P
GP6	238	7.814	15.914	P	P	P	P
GP7	238	7.213	14.690	F	P	P	P
GP8	229	4.171	8.494	P	F	F	P
GP9	221	9.150	18.635	P	P	P	P
GP10	227	10.123	20.617	P	P	P	P
GP11	237	11.632	23.690	P	P	P	P
GP12	231	11.941	24.319	P	P	P	P
GP13	203	3.982	8.120	F	F	F	P
GP14	214	7.010	14.276	P	P	P	P
GP15	211	6.812	13.873	P	P	P	P
GP16	221	3.991	8.128	F	F	F	P
GP17	237	4.671	9.513	P	P	P	P
GP18	218	7.776	15.837	P	P	P	P
GP19	214	6.914	14.081	P	P	P	P

Note: Area of contact is 491mm²

Bendability Test on Rods (IS 1599:1985)

Four various diameters of coated rods—8, 10, 12 and 16 mm—were tested for bending at 450 and 900 pounds per square inch. Each bent surface of the coating was examined after the bend for any signs of cracks, crevices, delamination, and discoloration caused by stress concentration at the bend using a magnifying glass. If any of these deficiencies or even just one of them were discovered, the assignment was classified as failing (F). The outcomes are displayed in Table .

From this table it can be seen that the coatings GP, GP1, GP3 to GP7, GP9 to GP12, GP14 and GP15 were passed in all diameter when bent to 90°. It indicates that all these coatings developed elasto-plastic nature of coating and thus attributed not to fail by bending to 90°. All other coatings have failed due to insufficient elastic nature of the dried film. In other words these coatings are slightly rigid and thus cracked as bending. However, all the twenty coatings have passed the test with 10mm diameter rods when bent upto 90°. Higher the diameter leads to higher stress concentration at the bent zone and causes cracking. It is also observed that no delamination of coating even in failed rods. This is due to excellent adhesion of the coating with the substrate.

Table Results of Bendability Test on Rods

S. No.	Designation of coating	8mm ^r		10mm ^r		12mm ^r		16mm ^r	
		45 ⁰	90 ⁰	45 ⁰	90 ⁰	45 ⁰	90 ⁰	45 ⁰	90 ⁰
1	GPR	P	P	P	P	P	P	P	P
2	GP1	P	P	P	P	P	P	P	P
3	GP2	P	P	P	P	P	F	P	F
4	GP3	P	P	P	P	P	P	P	P
5	GP4	P	P	P	P	P	P	P	P
6	GP5	P	P	P	P	P	P	P	P
7	GP6	P	P	P	P	P	P	P	P
8	GP7	P	P	P	P	P	P	P	P
9	GP8	P	P	P	P	P	F	F	F
10	GP9	P	P	P	P	P	P	P	P

11	GP10	P	P	P	P	P	P	P	P
12	GP11	P	P	P	P	P	P	P	P
13	GP12	P	P	P	P	P	P	P	P
14	GP13	P	P	P	P	F	F	F	F
15	GP14	P	P	P	P	P	P	P	P
16	GP15	P	P	P	P	P	P	P	P
17	GP16	P	P	P	P	F	F	F	F
18	GP17	P	P	P	P	P	F	F	F
19	GP18	P	P	P	P	P	P	P	F
20	GP19	P	P	P	P	P	P	F	F

Taber Abrasion Test

The taber abraser, which uses abrasives attached to two rubber wheels that are weighted against a rotating test panel, is frequently used to assess the abrasion resistance of any coatings, despite frequent criticism that it is overly harsh. (Gregorovich *et al.* 1992). Results are evaluated in terms of weight loss of the coating material. A Harder material need not give good abrasion resistance, and therefore hardness cannot be related to the abrasion resistance. However, it is reported that (Wicks *et al.* 1994) the higher the tensile strength of the coating film, the higher the abrasion resistance. Results of abrasion test carried out on all twenty coatings are given in Table 4.3. The coating GP12 shows very less weight loss followed by GP11, GP10 and GP 9. The very poor value was obtained for the coating GP16. The coating GP12 proved to be the best because it contains fly ash + Rice husk ash as pigments which means more SiO₂ content. This excessive SiO₂.

Content along with rigidly formed / cross linked geopolymer system offers poor wear loss. In coating GP16, the pigments and fly ash and ferrosilicon powder. This indicates insufficient SiO₂ content and unreacted ferrosilicon with the geopolymer binder. It can be concluded that the best four coatings against abrasion are GP12 GP11 GP10 GP9 However there is no appreciable weight loss among coatings noted.

Table Taber Abrasion Test (ASTM D 4060)

S. No.	Coating	Weight of panel before Abrading (A) g.	Weight of panel after Abrading (B) g	Weight loss (A - B) g	Wear index $\frac{A-B}{C} \times 1000$
1	GPR	62.801	62.598	0.202	0.202
2	GP1	63.134	62.886	0.248	0.248
3	GP2	63.099	62.848	0.251	0.251
4	GP3	62.894	62.631	0.263	0.263
5	GP4	62.963	62.667	0.269	0.269
6	GP5	63.016	62.844	0.172	0.172
7	GP6	62.943	62.749	0.194	0.194
8	GP7	62.896	62.731	0.195	0.195
9	GP8	63.134	62.951	0.183	0.183
10	GP9	63.016	62.853	0.163	0.163
11	GP10	63.103	62.964	0.139	0.139
12	GP11	62.949	62.828	0.121	0.121
13	GP12	62.862	62.752	0.110	0.110
14	GP13	62.749	62.552	0.197	0.197
15	GP14	62.813	62.614	0.199	0.199
16	GP15	62.944	62.743	0.201	0.201
17	GP16	62.896	62.623	0.273	0.273
18	GP17	62.792	62.493	0.299	0.299
19	GP18	63.001	62.727	0.274	0.274
20	GP19	63.012	62.742	0.270	0.270

No of cycles (C) = 1000. Wheel used CS-10, Vacuum level =60,

5. CONCLUSION

A systematic study on all the prepared twenty geopolymer coatings resulted the following observations

- The average thickness of the studied coating varies from 210µm to 238µm. Coating thickness above 210 µm has no role in performance only the ingredients has main role in protection.
- GP16 showed poor adhesion strength perhaps due to the presence of ferrosilicon and poor cross link formation. The multiple hydroxyl group in GP12 developed good adhesion with the steel plate and chemical anchoring in addition to mechanical anchoring of coating.
- The presence of rice husk ash in the coating formulation improved the drying and thus results tight bonding between the steel plate and coating. GP7, GP13 and GP16 were failed at 3mm diameter of the cone and passed at 6mm diameter of the same cone. Further all the other coatings were found to possess very good flexibility characteristics. The additives such as microsilica, rice husk ash do not possess required amount of aluminium oxide (Al_2O_3) for the dense cross linking and therefore poor flexibility. Also, during film formation, evaporation of water from the film lefts with micro voids and that reduces the strength against flexibility.
- The visco – elastic behavior of coatings was studied by impact loading test. It was found that three coatings namely GP13, GP16 and GP18 are failed. This fact may be attributed to the poor adhesive strength comparatively with others.
- Bendability test on coated rods of 12mm and 16mm diameter rods showed coating failure for GP2, GP8, GP13, GP16, GP17 and GP19. These coatings are not suitable when the rods are likely to be bent at the usage site.
- Pencil hardness test has been carried out on all the coated panels and the results suggested that all the studied coatings were passed in this test.
- Taber abrasion test result shows the lesser loss of materials found to be for the coatings GP11 and GP12. This was in consistence with the other test and found that these two coatings perform well in Taber abrasion test.
- Field exposure studies also give GP12 and GP11 as good coatings.
- GP10, GP11 and GP12 have performed excellently under salt spray test conducted for a period of 60 days (1400 hours). The performance

was attributed to the strong adhesion of between the plate and the coating.

In conclusion, GP10 (Binder + Fly ash + Clay + Iron oxide yellow) and GP12 (Binder + Fly ash + Rice husk ash + Iron oxide yellow) have passed all the examinations as per the experimental conditions adopted in the present study and may be very well utilized for preventing or decelerating the corrosion rate of steel rebars in concrete.

In future, the prepared geopolymer coatings will be subjected to various analytical characterizations studies such as X-ray diffraction to identify the crystallographic information, Scanning Electron Microscope with EDX to investigate the surface morphology and elemental composition, Fourier Transform Infrared and Raman Spectrometers to record the functional groups vibrations and X-ray Photoelectron Spectrometer to establish the chemical information of the constituents. These studies will be more useful to reveal the physical and chemical properties of the formulated coatings for anticorrosive applications.

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