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Comparative Study on Durability, Mechanical Strength and Ecology of Ferrocement Made from Geopolymer and Conventional Portland Cement Mortar

Baskara Sundararaj J*, Dhinesh M, Revathi.T, Rajamane N.P

Center for Advanced Concrete Research SRM University, India

Abstract : Ferrocement is a composite material composed of a mortar reinforced with steel fabric/mesh, used to form thin sections. Geopolymer is an innovative construction material prepared by utilizing the industrial waste materials like Fly ash, GGBS, Red mud, Rice husk ash etc... In the present study OPC with partial replacement of Fly Ash (25%, 50%) and geopolymer mortar were taken with the geopolymer mortar ratio of 1:2. And the liquid/binder ratio was 0.45. It was observed that ferrocement made by geopolymer mortar shown superior properties interms of strength,durability,fatigue,hightemperatureresistance,corrosion,etc. Corrosion was not observed even after 60 days of Alternate Wetting and Drying (AWD) cycles of Accelerated Corrosion Test. The test results show that flexural strength of geopolymer mortar increases with increase in volume fraction percentage and specific surface of steel mesh as compare to ferrocement mortar. The micro-structural changes were determined by FESEM. These new composites (Geopolymer mortar) can be used form a king precast elements such as casting of water tanks, innovative architectural aesthetic constructions, faster low cost durable houses, corrosion resistant pipes for sewage lines, tunnel linings in metrorail, roads and irrigation techniques. The present development of new ferrocement can become an apt substitute for conventional ferrocement, but with very low carbon footprint.
Keywords: Ferrocement, Geopolymer, wire mesh, Accelerated corrosion test, Durability, FESEM, EE, ECO2E.

Introduction:

Ordinary Portland cement(OPC) is one of the most essential binder material in the construction industry. It is estimated that the production of OPC, releases the large amount of Carbon-di-oxide (CO2) gas which subsidizes the 65% of global warming [1,2]. For the production of one ton of OPC emits approximately0.8 ton of CO2 in the atmosphere, thereby the cement industry produces 7% of all CO2 emission. Although the use of OPC is unavoidable in the construction industry, many efforts were made in order to find an alternative/to reduce the consumption of OPC.The research work is going in the utilization of accompanying cementious materials such as fly ash, GGBS, Red mud, rice husk ash, metakaolin as a binder in the construction world.In this aspects Davidovits coined a new innovative technology namely “Geopolymer” which shows a significant promise for application in the concrete industry, in terms of reducing the global warming through CO2 emission and also alternative to the OPC [3].Geopolymer mortar is an inorganic polymer prepared from the industrial waste by-products(Contains alumino-silicate) like fly ash and it is activated by the alkaline solutions[4].Class F fly ash based geopolymer matrix possess high mechanical strength, moderately low creep , possess excellent thermal resistant and also resistant to the acid, sulphate attack[5,6].

The two main constituents in the preparation of GP ferrocement are source material and alkaline liquid. The source material for GP ferrocement should be rich in aluminium(Al) and silicon(Si) and also availability, cost of the precursor material is very essential[8]. The most commonly used alkaline solution for the geopolymerisation is a hybrid combination of sodium hydroxide and sodium silicate solutions. Forming a shape with the required structure in the construction field a ferrocement is required. Ferrocement(FC) is an environmental friendly in nature and it also had a superior properties in terms of cracks control, impact resistance and toughness largely due to the closely spacing and uniform dispersion of reinforcement within the material [9] because of its light weight structural thin member, which is suitable for substituting wood and for structural elements of exotic shapes such as shells, chimneys, boats, etc [10-15].FC is an gorgeous construction methodfor its unique properties like tensile strength, fire resistant ,earthquake and corrosion compared to the traditional method. The main benefits of utilizing this FC in construction field are due to its light weight, minimummaintenance and long lifetime.

In the present study the ferrocement are made with conventional cement mortar with 25% and 50 % replacement of fly ash and geopolymer mortar. In the present study three types of conventional ferrocement and ferrogeopolymer mortar matrix were formulated .The matrix durability was studied by ACT method and ecological importance were studied in this research paper.

2. Materials:

2.1 Cement:

Generally, the ferrocement is prepared by using OPC.As per the Indian Standard IS 12269-1987 of grade 53 cement was used in the present study. The Physical Properties of solid materials has been done and it is tabulated in **table1.**

Table1 Physical Properties of Solid Source Materials

Material	Property	Result
OPC (Testsasper IS:4031)	Conforming BISCode	IS:12269
	Fineness Index(90µm sieve)	4.0%
	FinenessIndex(Blaine)	342 m^2/Kg
	SpecificGravity	3.13
	Normal Consistency	31%
	Initial settingtime	45minutes
	Compressive strength(IS:4031)	55MPa
	Final setting time	225minutes
Fly Ash	Conforming BISCode	IS:3812
	Type	Class F
	Fineness(Blaine)	342 m^2/Kg
	SpecificGravity	2.21
	Bulkdensity	1010kg/m^3
GGBFS	ConformingBISCode	IS:3812
	Fineness(Blaine)	425m^2/Kg
	SpecificGravity	2.91
	Bulkdensity	1100kg/m^3
Fine aggregate -Riversand	ConformingBISCode	IS:383
	FinenessModulus	2.5
	WaterAbsorption	0.8%
	SpecificGravity	2.51
	Bulkdensity	1610kg/m^3

2.2 Ground granulated blast furnace slag (GGBS):

The GGBS used in the study was obtained from JSW Cements ltd. The Specific surface area of the slag was 425m2/Kg. GGBS is an industrial waste product from Steel manufacturing Industry.

2.3 Fly ash:

In the present study class F fly ash obtained from Ennore power plant, Tamilnadu is used. The Specific surface area of the fly ash was 342m2/Kg. The chemical composition of powdery material was listed in **table2.**

Table2 Chemical Composition of Solid Source Materials

Component	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**Na_2O**	**CaO**	**MgO**	**K_2O**
Fly ash	47.5	33.4	10.1	0.01	2.09	0.1	1.6
GGBS	21.6	14.9	1.78	0.01	55.3	2.6	0.5
Cement	21.1	4.5	0.55	0.6	65.02	2.9	0.4

2.4 Fine Aggregate:

Fine aggregate is used to produce FC. Normal river sand with the fineness modulus of 2.45 was used as fine aggregate and it is obtained from nearby river beds. Based on the fine aggregate selection the consistency and compaction is achieved in the FC matrix.

2.5 Water:

Water is used for the hydration of the binder material(OPC). The pH of the water should be maintained as 7 and it should be free from organic and deleterious matter will fit for the construction purpose.

2.6 Activating solution(AS):

The combination of Na_2SiO_3(MR SiO_2/Na_2O: 2.0, wherein Na_2O 15%, $SiO_2$33% and H_2O 52%) and caustic lye (48% NaOH) were used in the study. The activating solution is prepared at least 24 hrs. prior to use. The physio-chemical properties of activating solution are listed in table3.

Table.3 Physio-chemical properties of activating solution

Chemical formula	$Na_2O:SiO_2$
Appearance	Liquid(Gel)
Color	Colorless liquid
Boiling point	102^0C for 40% aqueous solution
Specific gravity	1.58
Molecular weight	184-250
Density	1.54 kg/l

2.7 Steel wire mesh:

This Consist of one layer of steel wire mesh of 25 mm x 25mm gauge length and 3 mm thick, with tensile strength of 512N/mm^{2}coveredoneithersidebyalayerofchicken wiremeshof 0.5mm thickness with openingarea150 mm^{2}has been used as reinforcement

3. Experimental method and test procedure:

3.1Compression and Split tensile strength:

Plastic Cylindrical moulds of size:50mmdiameterx 100mm height was used to cast the specimens. Demoulding of these cylindrical moulds was done by cutting carefully the plastic with thick sharp steel cutting tool and the specimens were submergedinwater and airforcuring. Three mix proportions were used in the preparation of the ferrocement. Cement to sand ratio was fixed to 1:2 and the water to cement ratio was maintained as 0.45 for all the mixes. The cementious material (OPC) was replaced by 25% and 50% of fly ash. Mixing and curing were performed according to the ASTM C192-02. Eventually Three geopolymer mixes have been studied Geopolymeric source material (GSM: GGBS and Fly ash) to sand ratio was fixed to 1:2 and the Activating solution (AS) to binder was 0.45 for structural grades. The GGBS/ (FA+GGBS) 1, 0.75, and 0.5 are taken as GSM in the ferrogeopolymer mortar mixes. The GSM and fine aggregate were mixed together for 3-4 mins followed by the AAS in the mixer pan and mixing was continued for 5mins. The mix design is tabulated in table4

Table.4 Mix design of ferrocement mortar.

Mix Id	**Type**		**CM1**	**CM_2**	**CM_3**	**GM_1**	**GM_2**	**GM_3**
Binding Materials	Cement	%	100	75	50	-	-	-
	FA	%	-	25	50	-	25	50
	GGBS	%	-	-	-	100	75	50
AAS	Type	A Mixture of SHF and SSS						
	SiO_2/Na_2O	w/w	-	-	-	0.56	0.56	0.56
L/B Ratio	w/w	w/w	0.45	0.45	0.45	0.45	0.45	0.45
Materials Quantity kg/m^3	Cement	-	640	480	320	-	-	-
	FA	kg/m^3	-	160	320	-	160	320
	GGBS	kg/m^3	-	-	-	640	480	320
	Sand	kg/m^3	1280	1280	1280	1280	1280	1280
	Water	kg/m^3	256	256	288	-	-	-
	AAS	kg/m^3	-	-	-	256	256	288
Mix	Density	kg/m^3	2203	2197	2168	2200	2178	2121
Specimen Size	Dia	mm	50	50	50	50	50	50
	Height	mm	100	100	100	100	100	100
Curing			Water	Water	Water	Air	Air	Air

Table5. Basic Data For Ecology Computations

Material	**EE**	**ECO2e**	**Cost**
	MJ/Kg	kgCO2e/kg	Rs/kg
OPC	4.798	0.80	7
GGBS	1.600	0.083	3
Fly ash	0.1004	0.0104	1
Sand	0.081	0.00516	1.25
NaOH flakes	20.5	3.2	30
Na_2SiO_3	10.2	2.0	12
H_2O	0.25	0.001	1
Processing for Mortar with SSS (20%extracost)	0.014	0.018	0.5

Table6:Strength properties of FC/FGP mortar

Mix Id	**Compressive Strength fc (MPa)**				**Tensile strength ft (MPa)**	**Water Absorption (%)**
	7 Day	**14 Day**	**28 Day**	**90 day**	**28 Day**	**90 day**
CM1	17	28	30	32	3	8.9
CM2	17	28	32	33	4.1	8.5
CM3	15	21	24	26	3.9	7.9
GM1	33	37	40	40	3.9	7.2
GM2	37	40	42	45	4.1	7
GM3	27	34	39	44	3.9	6.5

The compressive strength and tensile strength data on an average of 5specimensof each mixes are given in **table6**.

3.2.Flexural strength of Ferrocement Beams:

A beam of size 500mmX100mmand50 mm thick is made with both conventional cement mortar and geopolymer mortar. The ingredients of mortar were mixed using an electrically operated mixer machine. The wooden mould of FC/FGC was filled fresh mortar mix with uniform distribution of reinforcement 1 layer of welded wire mesh covered with 2 and 4 layers of chicken mesh shown in **Fig1**. Vibration was almost not required since the mix used was self compacting in nature. The moulds were covered with wet gunny bag cloths after the bleed water of the mortar had just disappeared. The specimens were demolded after 24 hours andthensubmergedinwater and air forfurthercuring. Two point loads was applied on the beam to measure the ultimate load carrying capacity of the beam**Fig2.**

Fig 1.Casting of ferrocement and ferro geopolymer mortar beams

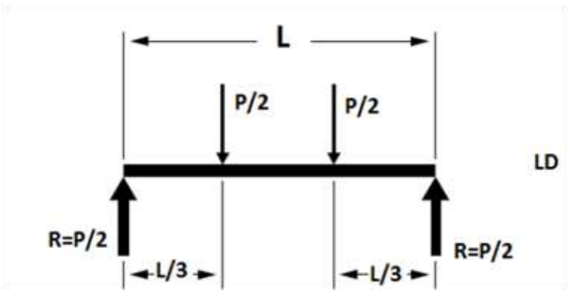


Fig 2 Two point load on beams

3.3.Structural load test of Ferrocement/Ferro Geopolymer panels/slabs:

The slabs of size1000mmx300mmand25 mm thickare madewith both conventional cement mortar and geopolymer mortar with the steel reinforcement of 3mm diameter welded wire mesh with 2 and4 layersof chicken mesh on either side of the welded wire mesh. Single point load was applied on both the slabs and measure the deflection with the corresponding loads **Fig3.**

Figure3:Testing of Ferrocementslabs

3.4. FESEM:

Environmental Scanning Electron Microscopy, ESEM, in combination with Energy Dispersive X-ray Spectroscopy, EDS (Quanta 200FEG SEM, operating at 30 kV in the low vacuum mode using a back scattering detector) were performed on external surfaces (depth 1 mm from the external surface) of concrete. The samples for the analysis of cross section were then impregnated under vacuum with a low viscosity epoxy resin and polished before the observation. The SEM with EDS analysis were performed for the specimens cut from the cube after curing for 28 days.

3.5: Accelerated Corrosion Tests:

As Portland cement matrix and Geopolymer matrix provides excellent optimum alkaline environment (pHrangingfrom12.6to13.5) so that the steel remains protected from corrosion. Thus, there is a need for adoption of a suitable corrosion testing method for gettingthetest data withinshort duration oftime.

Towards this, Alternate Wetting and Drying (AWD) Cycles were adopted; Each cycle consisted of 16 hours of soakingin5% NaCl solution followed by oven drying of the specimens at 60ºC for8hours. The oven dried specimens were cooled to room temperature before soaking them againin5%NaCl solution. OPC and GPC panels are made with size of (150mmx150mmx25mm) with the Powdery material: sand ratio is 1:2 with 0.45 Liquid/solid ratio **Fig4& Fig5.**TheFC specimens were cured only for 3 days in water and then air dried for 3 days before subjecting them to ACT-AWD. The Ferro Geopolymer was cured only 3 days in atmospheric air before subjecting them to ACT-AWDFig5 & **Fig6**. This short curing period of water was adopted to generate porous matrix so that faster corrosion of embedded steel is made feasible.

Fig4:Ferro cement panels

Fig 5: Panels left for drying

Fig6: Soaking in 5% NaClSol

Fig 7:Oven dried at 60ºC

Fig8. Electrochemical Potential Measurement using Saturated Calomel reference Electrode and Multimeter

3.5.1 Visual Observation Test:

The AWD cycle is done by allowing the specimens to oven dry at 60°c for 8 hours and then soaking in 5% NaCl for 16 hours in **Fig7**. Before placed in NaCl solution the specimens were cooled to room temperature. Every 5 cycles the corrosion spots in the specimen is observed by visual observation.

3.5.2 Electrochemical Potential Measurements:

Calomel Electrode was used as reference electrode to measure the Electro chemical potential (ECP) the embedded steel and the Reference Calomel Electrode were kept on the surfaceofthespecimens to measure the potential **Fig8**. Morepositive of ECP is expected to represent lower rates of corrosion.

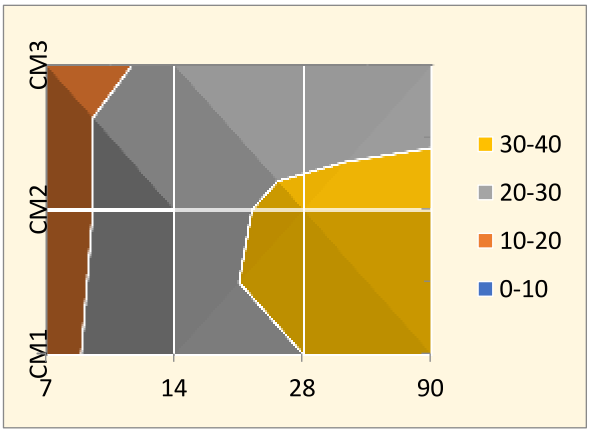
3.6. EcologyofFC and FGC Mixes:

Using the basic data given in**Table5**, the Embodied Energy(EE),Embodied CO2 Emission (ECO2e) and the cost economics contents ofFC mixes and Ferro Geo mixes werecomputed.

4. Results and discussion:

4.1.Compressive strength:

The compressive strength of ferrogeo polymer matrix was increased by 25-30% of 28 days and 90 days of curing (**Fig9 & Fig 10**).Eventually geopolymer matrix attains maximum strength after 7 days of curing.The test results are tabulated in **table6.**Lesser water absorption was observed in Geopolymer matrix.



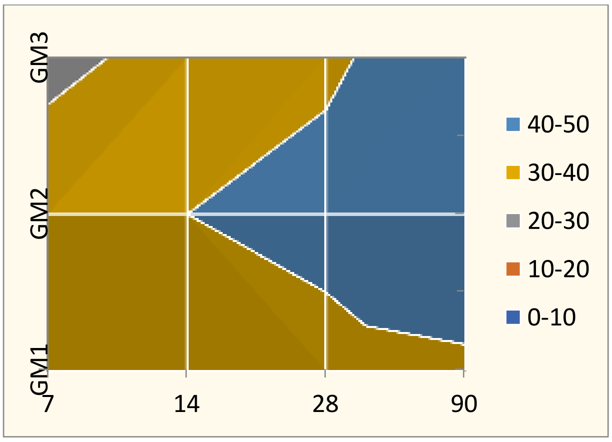


Fig9 Conventional cement mortar (CM) strength Compressive strength

Fig 10 Geopolymer mortar (GM) Compressive

4.2 Flexural strength of Ferrocement Beams:

The test results of two points loading there is no change in flexural behavior of FC and FGP matrices in terms of initial and ultimate carrying capacity. The flexure failure of the beam section as shown in Fig11 and the test results are tabulated in **table7.**

Table7 Flexure test on Ferrocement Beam

Mix Id	Type		CM1	CM_2	GM_1	GM_2
Two point loading test on Beam (500x100x50mm) 2 Layer	First Crack Load	KN	3	3	3	3
4 Layer	First Crack Load	KN	3	4	4	3
2 Layer	Ultimate Load	KN	5	5	6	6
4 Layer	Ultimate Load	KN	6	6	6	6

Table 8. Structural load test of Ferrocement/Ferro Geopolymer panels/slabs:

Mix Id	Type		CM1		GM_1		GM_2	
Flexure Test on FC Slabs (1000mmx300mmx25mm)			E	T	E	T	E	T
2 Layer	Deflection @ **P=4KN**	mm	3.8	5.67	0.69	5.04	0.68	4.79
4 Layer		mm	4.23	5.67	0.49	5.04	0.69	4.79
2 Layer	Deflection **@ P= 8KN**	mm	7.65	11.65	1.2	10.09	1.28	9.58
4 Layer		mm	8.58	11.65	1.13	10.09	1.37	9.58
2 Layer	Deflection **@ P= 12KN**	mm	10.7	17.03	1.86	15.12	2.04	14.37
4 Layer		mm	12.7	17.03	1.74	15.12	1.95	14.37

E – Experimental Value
T – Theoretical Value

Figure11:Initial crack and Failure of beam

4.3.Structural load test of Ferrocement/Ferro Geopolymer panels/slabs:

The observed test results of the Ferrocement and ferrogeopolymer slabs are tabulated in **table8.** The result indicates that the readings obtained from the experiments showing lesser deformation than the actual calculated theoretical deformations. The difference between actual theoretical and experimental deformation was about 60-70% higher in ferrocement panels and 500-700% in ferrogeopolymer panels. As a result ferrogeopolymer panels are high stiffness material than the conventional ferrocement panels.

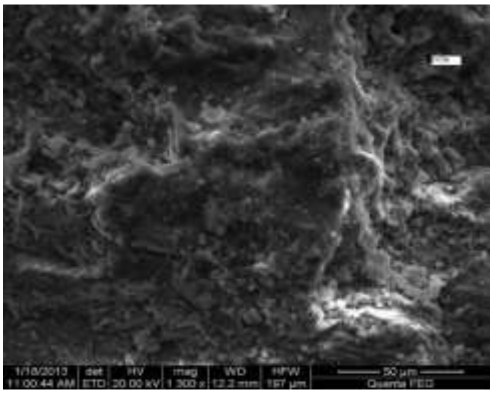
Theoretical Deformation of the ferrocement / ferrogeopolymer slabs were calculated by using the formula

$§= PL^3/48EI$

Where,
§= Deflection of the slab corresponding to the applied load
P = Applied Live load to the Slab
L = Effective Length of the slab
E = young's Modulus of the slab
I = Moment of Inertia of the member
Here E= Es + Ec
I= Is + Ic

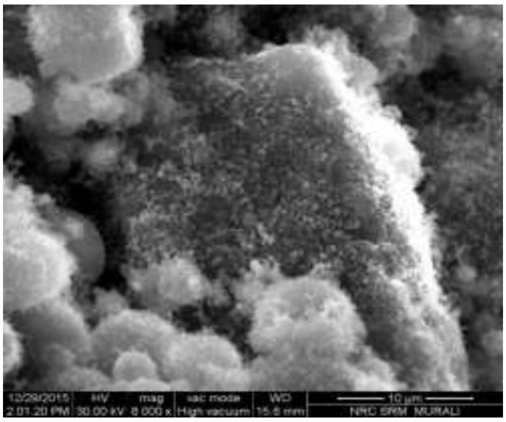
4.4FESEM:

Calcium silicate hydrate plates and calcium hydroxide crystals were clearly identifiable in the CM1 specimen. Well compacted rods and grains are typical hydration products of mature cement paste. (Fig 12.0) Dense micro structure does not allow the diffusion of chloride content. From **Fig.13** it is observed that most of the slag particles are dissolved by the reaction generating solution. The dense micro structure with micro cracks was observed it is due to the formation of C-S-H gel. From the **fig. 14** it is observed that there is unreacted fly ash particle with spherical shape. The microstructure was improved after 28 days it is due to the slow dissolution of fly ash particle in the reaction generating solution and it is reflected in the mechanical strength property.



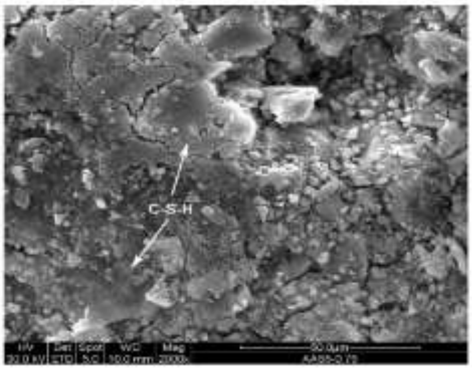
Element	At.Wt %
C	23.5
O	36.2
Al	7.8
Si	10.7
Fe	0.74
Ca	21.4

Fig 12:SEM and EDS of CM1 matrix



Element	At.Wt(%)
Na	2.7
Ca	33.4
Al	4.5
Si	8.7
O	32.2
C	18.5

Fig 13. SEM and EDX of GM1



Element	At.Wt%
C	44.19
O	44.91
Al	00.79
Si	02.93
Ca	06.90
Fe	00.29

Fig 14. SEM and EDAX of GM2 matrix

Figure15:Corrosion spots observed in specimens

4.5 Corrosion test:

4.5.1 Visual Observation Test:

Visual observation of corrosion spots was done on every 5 cycles of AWD. After 90 and 180 cycles of AWD the specimens made with ferrocement matrix shows more corrosion spots than the ferrogeopolymer matrix **fig15** and the results are tabulated in **table 9.** Generally sodium silicate provides more protection to the steel reinforcement for the initiation of the corrosion.

Table 9. Test Data after Accelerated Corrosion Testing

Mix Id	Visual Corrosion Spots ACT-AWD Each Cycle of ACT-AWD = Soaking 5% NaCl for 16hrs + Drying at 60°C for 8hrs			ECP Value (mv)
	60 Cycles	90 Cycles	180 Cycles	90 Cycles
CM1	2	4	6	-190
CM2	0	2	4	-186
CM3	0	1	2	-170
GM1	0	2	3	-160
GM2	0	1	2	-154
GM3	0	0	1	-145

4.5.2 Electro Chemical Potential Measurement

The potential shift is a function of the durability of the protective layer on steel surface. Thus, the corrosion potential of rebars in concrete is a good indication of either the depassivation or activation of corrosion. The corrosion potential measurements against SCE is given in Table 9.0 TheECPof-160mVrecordedinFGPmatrix andthis valueisless negative as compared to -190mV of mix FC. According to the guidelines involved in ASTM C876-87 the probability of corrosion initiation is greater than 90% when corrosion potentials are more negative than(-350 mV) relative to the copper–copper sulfate (CSE) and -270 mV relative to the Saturated Calomel Electrode. There was a 15-20% was reduced potential was observed in ferrogeopolymer matrix.

4.6. EcologyofFC and FGC Mixes

Using the basic data given in **Table 5**, the Embodied Energy (EE) and the EmbodiedCO_2Emission (ECO2e) contents ofFC mixes and FGP were computed and are given in **Table10**; the cost analysis is also worked out. The calculated values indicate that EE of FC mix is 3270MJ/m3 and this value reduces to 2250MJ/m3 in case of FGP mix and thus FGP requires less energy to produce. The ECO2e contents of 559 and 284kg CO2e for mixes FC and FGP indicate that FGP accounts for lower quantity of emission of Green House Gas. Thus, FGP is highly eco-friendly material. Eventually 90daystrengthofFGPis higheras40MPa than the 30 MPa of FC matrixes. The actual production cost of per metre^3 of FGP matrix is 17% lesser than the production of FC matrices.

Table10.EcologyofFC and FGC Mixes

MIXID	CM1	GM1	%change	Remarks
Cement kg/m^3	640	-		
GGBFS kg/m^3	-	640		
Sand kg/m^3	1280	1280		
NaOH flakeskg/m^3		25.6		
Na2SiO3 kg/m^3		51.2		

DW kg/m^3	256	179.2		
Density of the matrix	2203	2200	-	Almost similar self weight
90daystr, f_{c90d} MPa	30	40	25	Higher strength of matrix
EE=Embodied EnergyMJ/m^3	3270	2250	32	Lower Embodied Energy
ECO_2e $kgCO_2e/m^3$	559	284	50	Lower CO_2Emission content
CostRs/m^3	7438	6181	17	Lower cost

5. Conclusion:

The ferrogeopolymer shows 25-30% increase in the mechanical strength property compared to that of OPC. The ferrogeopolymer shows 85% increase in the deflection at a higher load (1600Kg).Inclusion of fly ash shows does not affect the flexural strength compared with that of ferrocement. It is observed that there is an increase in the corrosion spots in the 90thcompared with that of ferrogeopolymer with the untreated mesh in ACT-AWD .The positive value of EP indicates that ferrogeopolymer has low corrosion rate compared to that of ferrocement. The overall results reveals that ferrocement slab and panels shows good performance in engineering aspects and well suited for the construction field in the developed and developing countries.

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