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TECHNICAL PAPER

Innovative sustainable coconut husk mortar for ferrocement infrastructure solution

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Abstract
Coconut husk (CH) is the by-product of crushing raw coconut shells (CS). Utilization of CH as a sustainable replacing material for the river sand in the production of mortar for the purpose ferrocement application is tried in this study. This novel idea of using CH waste, not only produces the green mortar, but it also minimizes landfills' area of dumping CS waste. Ferrocement occupied by the mortar nearly 95% volume of ferrocement products. Mortar produced using CH in the place of river sand and its application in ferrocement is very limited. Therefore, this study aimed to produce mortar using CH as fine aggregate in the place of river sand and concentrated to develop the mortar compressive strength minimum of 35 N/mm^2 as per ACI standard and WRD handbook. Therefore, an experimental study was conducted through trial mixes to achieve the target strength of CH mortar, and for comparison purposes, conventional mortar was produced for the same target strength. Thirty-two trial mixes in total were produced. Since the main aim of this study is to produce CH used mortar for the target strength and hence achieved after many trials with different combinations of admixtures. To show this study is an innovative sustainable infrastructure solution and feasible to implement infield practice, samples of ferrocement panels were produced from the selected trail mixes.

Keywords Coconut husk · Mortar · Ferrocement · Panels · Application

Introduction

Ferrocement is one of the composite structural materials. Compared to the cross section of structural elements slab, beam, and column, ferrocement elements are very thin in cross section. Ferrocement consists of cement mortar and reinforcement by many closely placed layers of steel wire mesh [1]. It has become the basis for modern reinforced concrete, and it was invented in France and the Netherlands in the early 1840s. Since there are contrasts between cement and concrete and hence used interchangeably. When ferrocement was invented in the mid-nineteenth century, the meaning of cement changed. The original name was given to the reinforced concrete at least since the 1890s as ferro-concrete. Ferrocement has comparatively better strength and impact resistance. It provides superior resistance to corrosion, earthquake, and fire than conventional materials, and hence, almost equal weightage is given to ferrocement [2]. The excessive use of construction materials like ferrocement has created serious environmental concerns in many regions. This leads to natural aggregate resources getting exhausted. Hence, it is necessary to find alternate aggregates in an urgent manner. The sustainability issue has necessitated the need for research towards finding sustainable alternatives to save natural resources.

The important constituents in ferrocement are mortar which is a paste consisting of cement, sand, and water. Sand provides mass to the ferrocement, decreases shrinking and results in the economy of construction. It is necessary for anyone studying ferrocement to know more about mortar. The study of ferrocement is incomplete if it does not include the mortar in depth and range. Generally, natural river sand is used as fine aggregate in ferrocement production through the years. But with increasing usage of river sand both legally and illegally, several rivers have been mined to a maximum, and there are cases where construction has to be stopped because of the unavailability of river sand. It is important in this context to find alternate fine aggregates that can replace river sand thus protecting the natural resource. If

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this aggregate comes from materials considered as wastes it is an additional benefit. In general, any kind of waste can be used for finding alternative material, so that it may lead to dual advantages. One is that the waste generated is used as an alternative sustainable material in concrete and the other advantage is that these generated waste are disposed of and minimized their landfill area [3–10].

Materials used

This section provides about the materials used in this study such as coconut husk, other materials used, and materials properties.

Coconut husk

Coconut is widely cultivated around the world in more than 93 countries, with Indonesia, the Philippines, and India accounting for more than 80% of the world coconut production [11]. After coconut fruit is removed, the hard shell is normally thrown away, and this accounts for a great percentage of domestic waste volume in many tropical countries. Figure 1a illustrates the fresh coconut shell filled in a yard in one of the coconut industries from where it was collected for this study, and Fig. 1b illustrates the crushed coconut husk (CH) using the crusher specially developed and erected in the institute. Statistics on the top ten makers of coconut on the earth during the year 2019 are presented in Table 1. CS constitutes more than 60% of the solid waste volume generated domestically in India [11–16].

Table 1 Global top ten coconut producers, 2019 [13]

Country	Produced (MMT)
Indonesia	17.13
Philippines	14.77
India	14.68
Sri Lanka	2.47
Brazil	2.33
Vietnam	1.68
Mexico	1.29
Papua New Guinea	1.19
Thailand	0.81
Malaysia	0.54

Other materials used

As per the guideline, the compressive strength of mortar to be used for most of the ferrocement applications should not be less than 35 N/mm^2 [17–19]. Using conventional materials is not a problem of bringing the mortar strength 35 N/mm^2, but it was found in the case of using coconut husk. From the trail mixes carried out, it was found that the 100% replacement for river sand by the coconut husk is somewhat difficult to attain the minimum compressive strength of mortar 35 N/mm^2. Therefore, some of the supplementary materials are also tried in addition to coconut husk. In this study, ordinary Portland cement (OPC) Grade 53 affirming to the Indian Standard IS 12269: 2013 was utilized [20]. Silica fume confirming to IS 15388:2003 [21], ground granulated blast furnace slag (GGBS) confirming to IS 12089:1987 [22], fly ash conforming to IS 3812 (Part 1):2013 [23], and ferrock (it is prepared with 60% of iron powder and remaining 40% using different combinations of materials like fly ash/limestone powder/silica fume/glass powder/metakaolin with oxalic acid) as suggested in the literature [24, 25] are the other supplementary cementing materials used in this study. Also, in some trials, crimped steel fibre and brass-coated steel fibre both having a length of 13 mm are used to attain the target mortar strength of 35 N/mm^2. A chemical admixture sulfonated naphthalene polymers-based superplasticizer (SP 430), and solution 145 which is the combination of sodium chloride (NaCl), sodium hydroxide (NaOH), and water is also used for the purpose of enhancing the workability of the mortar. The potable water free from contamination was utilized for the whole process of producing ferrocement mortar and also for curing.

Fig. 1 **a** Fresh coconut shell **b** Crushed CH

Materials properties

River sand was used for the study as the fine aggregate conforming to grading zone II as per IS 383:2016 [26] for control ferrocement. Crushed CH particle sizes were also compared through sieve analysis and found that it conformed to grading zone III as per IS 383:2016 [26]. The river sand and CH specific gravity are 2.58 and 1.14, respectively. The bulk density of river sand and CH is 1665 and 575 kg/m^3, respectively. The graph drawn between the particle sizes and the percentage passed by both river sand and CH is shown in Fig. 2. The aspect ratio of crimped steel fibre and brass-coated steel fibre is 26 and 52, respectively. Since CH is a

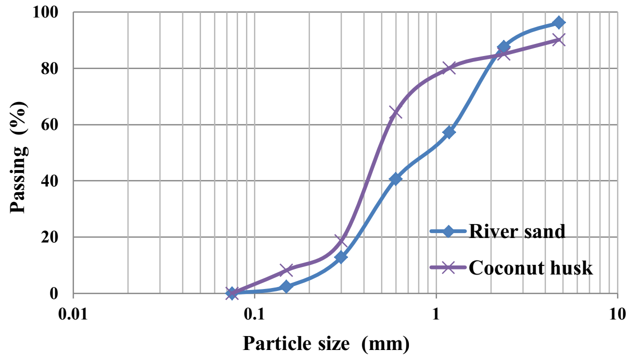

Fig. 2 Sieve analysis results of river sand and CH

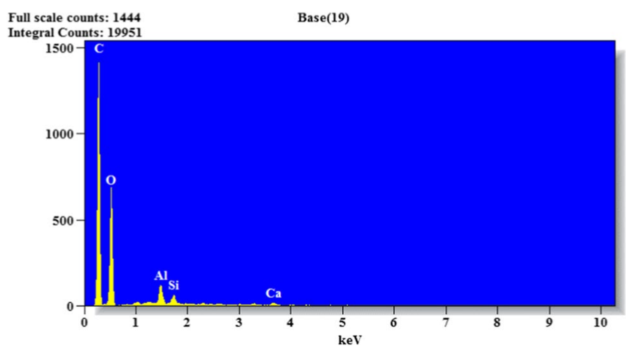

Fig. 3 EDX analysis of CH

new material tried in place of river sand, chemical elements present in it are found through energy dispersive X-ray analysis (EDX) and the same is illustrated in Fig. 3.

In general, CH consists of cellulose, semi-cellulose and lignin molecules. Cellulose, semi-cellulose and lignin molecules consist of carbon, hydrogen and oxygen atoms. EDX is capable of detecting all stable elements with the exception of hydrogen, helium, and lithium. The EDS (Fig. 3) of CH shows the strong peaks for carbon (49.93%), oxygen (48.30%) and weak peaks for aluminium (1.09%), silica (0.47%) and calcium (0.21%), put together 100%. The EDS seems to have an agglomerated expansive gathering of particles of carbon, oxygen, and others. The EDS clearly shows that there are no traces of iron particles in CH. Figure 3, EDX image given here rightfully, represents the higher percentages of carbon and oxygen atoms.

Methods

In this study, at first, trials were done using mortar making use of conventional materials like cement and river sand for the target strength 35 N/mm^2 without any difficulty within four trials. But, it was found hard in the case of mortar making use of cement and CH for the target strength 35 N/mm^2 hence tried many trials with different combinations of different materials including chemical admixtures by considering both workability and strength. To test the compressive strength of the mortar, the size of cube specimen 70.6 × 70.6 × 70.6 mm was used as per the standard IS 4031 (Part 6): 1988 [27]. For each trial, nine cubes cast and tested three cubes at 3, 7, and 28 days, respectively, for the compressive strength and the average of three cubes results are presented.

Trail mixes

To start with, guidelines suggested in the ACI code [17, 18] and another handbook WRD [19] were taken as a reference for mix proportioning. It was suggested in these references that the ratio of sand to cement by weight is 1.5 to 2.5 [17, 18], 1:1.5 to 1:4 [19] and the water–cement ratio by weight is 0.35 to 0.50 for the most common applications of ferrocement. To differentiate the identification of mortar mix trials notations are used as given in Table 2.

Table 2 Notations and indications followed

Notations used	Indications	Notations used	Indications
C	Cement	BSF	Brass-coated steel fibre
S	Sand	CH	Coconut husk
M	Mortar	SiF	Silica fume
Numbers	Trial numbers	G	GGBS
w/c	Water–cement ratio	FA	Fly ash
F	Ferrock	SP	Superplasticizer
SF	Steel fibre	SL	Solution 145 (Chemical)
IP	Iron powder	LSP	Lime stone powder
GP	Glass powder	OA	Oxalic acid
MK	Metakaolin	–	–

Materials used trials

As mentioned earlier, conventional mortar using conventional cement and river sand was tried at first in the ratio 1:2; 1:2.5; 1:3; and 1:4 and designated as CSM1, CSM2, CSM3, and CSM4, respectively. In the first three trials, the w/c ratio of 0.50 was kept constant, and in the fourth trial, the w/c ratio of 0.55 was used on the aspect of workability consideration. Then, CH material in trial mix ratio 1:3 and designated as CCHM1 with the requirement of w/c ratio 0.60 on the aspect of workability. But it gave approximately only 17% of the expected target strength. Therefore, it was thought that the use of ferrock in place of cement and 100% CH in place of river sand and hence done the trial mixes. Since ferrock was used in place of cement, the same was also tried with 100% river sand. But it would not be possible to achieve 35 N/mm^2 using 100% CH even if it is used in a 1:1 ratio; therefore, it was decided and used a different combination of other materials proportions with CH100% and is presented in Table 3. It was found that with 100% CH even with different combinations of other materials, it is not successful towards the target strength. Therefore, it was decided to go for partial replacement of CH for river sand with steel fibres and some trials are done and the same is presented in Table 4. The discussion on these trials is discussed in Sect. 4 "Results and discussions". Since steel fibres are used in CH mortar, for comparison purpose, steel fibres (6%) are also tried with conventional mortar (CSM3), designated as CSSFM1.

Specimen preparation

Mortar constituents were weighed, batched and mixed in a drum-type mixer machine. Fresh mortar prepared was poured in three layers into the moulds and tamped to minimize the air and void contents in the mortar specimen. Different materials used in the preparation of different mortar mixes are shown in Fig. 4.

The preparation of mortar and mortar cubes is traditional and not unique. However, the use of CH in making mortar is a novel idea, and to smell the same in comparison with conventional mortar, typical samples prepared are shown in

Table 3 Trial mixes using CH and other materials

Mix ID	Mix ratio	C	SiF	S	G	FA	F	CH	w/c	SL
CSiFCHM1	1:3	50%	50%	–	–	–	–	100%	0.6	–
CSiFCHM2	1:3	50%	50%	–	–	–	–	100%	–	0.65
CCHM2	1:3	100%	–	–	–	–	–	100%	–	0.65
GFACHM	1:3	–	–	–	50%	50%	–	100%	–	0.55
SiFGFACHM	1:3	–	10%	–	45%	45%	–	100%	–	0.55
CGFACHM	1:3	50%	–	–	25%	25%	–	100%	–	0.65
FCHM1 to FCHM4	1:3	–	–	–	–	–	100%	100%	0.5	–
FSM1 to FSM4	1:3	–	–	100%	–	–	100%	–	0.5	–
FCHM1 and for FSM1: F→IP+FA+LSP+MK+OA										
FCHM2 and for FSM2: F→IP+FA+LSP+SiF+OA										
FCHM3 and for FSM3: F→IP+GP+LSP+SiF+OA										
FCHM4 and for FSM4: F→IP+GP+LSP+MK+OA										

Table 4 Trial mixes using CH in partial and steel fibres

Mix ID	Mix ratio	C (%)	S (%)	CH (%)	SF	BSF	w/c	SP
CSCHM1	1:3	100	50	50	–	–	0.5	–
CSCHM2	1:3	100	60	40	–	–	0.5	–
CSCHSFM1	1:3	100	50	50	2%	–	0.5	–
CSCHSFM2	1:3	100	50	50	4%	–	0.5	–
CSCHSFM3	1:3	100	50	50	6%	–	0.5	–
CSCHSFM4	1:3	100	60	40	2%	–	0.5	–
CSCHSFM5	1:3	100	60	40	4%	–	0.5	–
CSCHSFM6	1:3	100	60	40	6%	–	0.5	–
CSCHSFBSFM1	1:3	100	50	50	6%	6%	0.5	–
CSCHSFBSFM2	1:3	100	60	40	6%	6%	0.5	–
CSCHSFM7	1:3	100	60	40	6%	–	0.35	1%
CSCHSFM8	1:3	100	60	40	6%	–	0.4	1.5%

Fig. 4 Materials used for mortar

Fig. 5 for the benefit of the readers. Keep the mortar-filled cube moulds under the coverage of the plastic sheet for 24 h. At the close of this age, detached them from the moulds and instantly placed them in fresh water and kept them till prior to testing. The water used for curing cubes was renewed every day and maintained at a standard room temperature of 27 ± 2 °C. The cubes were tested on their sides without any packing between the cube and the testing rig of the compression testing machine. To test the cube through the compression testing machine, the load was steadily uniformly applied, starting from 0 at a rate of 35 N /mm^2 /min.

Results and discussion

Since the main scope of this study is to attain the target strength of both mortars prepared using cement and sand and cement and CH expecting good workability, not much importance was given on the other parameters. However, wherever necessary the observations made are discussed in this section.

Workability of trial mixes

Maintaining plasticity is the most significant design criterion for ferrocement mortars, and the mortar mix should be as stiff as possible. Fresh mortar slump should not be more than 50 mm in general [17–19]. In this study, it is not found any workability issues in the case of both conventional materials and CH used mortar with different combinations of other materials in all the trials and the slump values are found to be less than 50 mm except in the cases CCHM2, SiFGFACHM, and CGFACHM mixes. These three mortar mixes CCHM2, SiFGFACHM, and CGFACHM gave very poor workability and experienced consolidation problems.

Density and compressive strength

The fresh and hardened concrete properties of conventional mortar using conventional cement, river sand, and steel fibre are presented in Table 5. Similarly, mixes produced with ferrock, coconut husk, and river sand properties are presented in Table 6. Likewise, mixes produced with CH, and other different materials combinations properties are presented in Table 7.

In the case of conventional materials used, trial mixes show the traditional way of directly proportional in increasing the density as the percentage proportion of river sand increases and indirectly proportional in the item of compressive strength. The identical trends were also observed in the item of mixes produced with CH. Also, depending upon the other material combinations followed are shown their densities ups and down. However, the traditional way of increasing density from fresh concrete state to 3, 7, and 28 days was

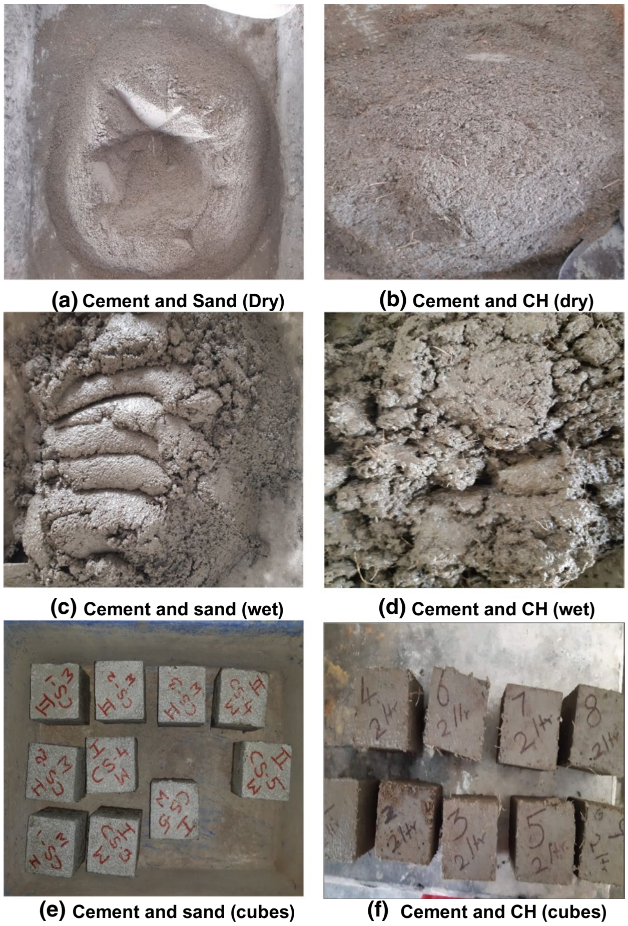

Fig. 5 Making mortar and cubes

found in all the trial mixes (Tables 5, 6, and 7). The same trends have been found in the case of compressive strength also. It can be noticeable that the density of the CSM3 (1:3) mix at 28 days is 2310 kg/m^3, and at the same time, the density of CCHM1 (1:3) mix at 28 days is only 1440 kg/m^3 which is approximately 38% lesser in comparison to CSM3 mix. Therefore, in the case of non-structural ferrocement elements where the strength is not the significant criteria, then this CCHM1 mix can be adopted so that the self-weight of that element could be reduced.

Since the main aim of this study is to develop a mortar for ferrocement application as per the literature [19] having compressive strength of 35 N/mm^2 and hence from the trail mixes carried out some selected mixes satisfying the strength criteria are given in Table 8.

The reason for the selection of mortar mix CSM3 is that this mix constitutes 100% cement and 100% river sand in the ratio of 1:3 gives the compressive strength 37.00 N/mm^2. Then, the selection of mortar mix CSCHSFM8 is that this the mix produced more than 35 N/mm^2 (i.e.) 36.10 N/mm^2 CSCHSFM8 in combination with CH and other materials including 6% steel fibre. Since only CH and other materials including 6% steel fibre alone give the required strength and also to study the effect of steel fibres in further studies, the mix CSSFM1 is also selected. Also, in the case of mix CSCHSFM8, only 40% CH was used and the remaining 60% is river sand, it was thought that the use of only 40% CH may not be effective utilization CH waste, and hence, to study the effect and use of 100% CH in further studies, the mix CCHM1 is selected though its 28 days strength is only 5.90 N/mm^2 so that it may be possible to apply for some non-structural ferrocement elements.

It was noticed that the failure of CH used mortar cubes is ductile in nature compared to the brittle nature of the failure of conventional materials used mortar cubes. This could be visualized through Fig. 6 (failure of CH used mortar cubes) and Fig. 7 (failure of conventional materials used mortar cubes). This ductile nature of the failure of CH used mortar mixes is an advantage in seismic zone areas.

Applications

The success of any research is recognized only when it is implemented in field applications. Therefore, to show this novel idea of using coconut husk mortar in the production of ferrocement, it was tried to produce a ferrocement panel of size 0.60 × 0.60 × 0.025 mm using both the mixes

Table 5 Fresh and hardened concrete properties (Conventional mortar)

Mix types	Fresh concrete density (kg/m^3)	3 days		7 days		28 days	
		Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)
Conventional mortar							
CSM1	2130	2235	28.10	2245	32.30	2280	42.60
CSM2	2155	2240	25.75	2260	29.70	2305	41.75
CSM3	2210	2260	23.20	2275	28.35	2310	37.00
CSM4	2255	2285	19.65	2305	26.10	2325	33.15
CSSFM1	2285	2295	19.25	2310	26.15	2340	38.80

Table 6 Fresh and hardened concrete properties (Ferrock, CH, and river sand)

Mix types	Fresh concrete density (kg/m^3)	3 days		7 days		28 days	
		Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)
Mixes produced with Ferrock and CH							
FCHM1	1140	1155	01.15	1160	01.30	1185	01.45
FCHM2	1120	1130	00.85	1150	01.05	1160	01.20
FCHM3	1145	1160	01.20	1170	01.40	1175	01.60
FCHM4	1160	1165	00.95	1180	01.25	1185	01.35
Mixes produced with Ferrock and River sand							
FSM1	2200	2210	01.25	2215	01.40	2245	02.35
FSM2	2215	2230	00.90	2240	01.00	2245	01.05
FSM3	2230	2245	01.35	2255	01.55	2265	01.90
FSM4	2240	2250	01.00	2270	01.15	2275	01.30

Table 7 Fresh and hardened concrete properties (Cement, CH, and others)

Mix types	Fresh concrete density (kg/m^3)	3 days		7 days		28 days	
		Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)
Mix used with CH							
CCHM1	1360	1385	02.35	1390	02.60	1440	05.90
Mixes using CH and other materials							
CSiFCHM1	1375	1390	01.80	1400	01.85	1410	02.55
CSiFCHM2	1425	1445	04.55	1460	05.75	1495	06.75
CCHM2	1415	1435	05.75	1465	09.60	1475	14.40
GFACHM	1365	1380	01.40	1395	02.65	1405	03.50
SiFGFACHM	1375	1425	01.25	1440	03.20	1495	05.00
CGFACHM	1380	1435	03.30	1460	05.55	1500	09.75
CSCHM1	1910	1935	09.35	1940	12.30	1950	17.15
CSCHM2	1935	1945	08.90	1965	11.15	1980	15.60
CSCHSFM1	1920	1955	10.45	1975	14.35	1985	20.15
CSCHSFM2	2000	2010	10.90	2040	15.10	2070	22.05
CSCHSFM3	2110	2115	12.85	2140	16.15	2145	26.65
CSCHSFM4	2085	2095	15.05	2115	20.85	2130	27.10
CSCHSFM5	2130	2140	14.30	2160	18.75	2180	26.90
CSCHSFM6	2175	2185	16.95	2210	21.75	2235	27.35
CSCHSFBSFM1	2195	2205	14.00	2215	17.40	2225	25.60
CSCHSFBSFM2	2220	2240	17.55	2255	19.75	2290	28.90
CSCHSFM7	2180	2190	21.45	2205	30.90	2225	44.55
CSCHSFM8	2150	2170	22.15	2175	29.50	2180	36.10

CCHM1 and CSCHSFM8 (Fig. 8) to showcase that this is possible to use in field applications in the near future. For the information to the readers, though the coconut husk has been used as a fine aggregate in mortar and tried to implement ferrocement slabs to prove its application, the structural and functional tests would be conducted and studied in the near future.

Conclusions

Coconut husk is replaced as a sustainable material in the place of conventional sand in the production of mortar for ferrocement application. As per the ACI 549.1R-93 and WRD handbook, it achieved the target compressive

Table 8 Selected mixes for ferrocement application

Mix types	Fresh concrete density (kg/m^3)	3 days		7 days		28 days	
		Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)	Density (kg/m^3)	Strength (N/mm^2)
CSM3	2210	2260	23.20	2275	28.35	2310	37.00
CSSFM1	2285	2295	19.25	2310	26.15	2340	38.80
CSCHSFM8	2150	2170	22.15	2175	29.50	2180	36.10
CCHM1	1360	1385	02.35	1390	02.60	1440	05.90

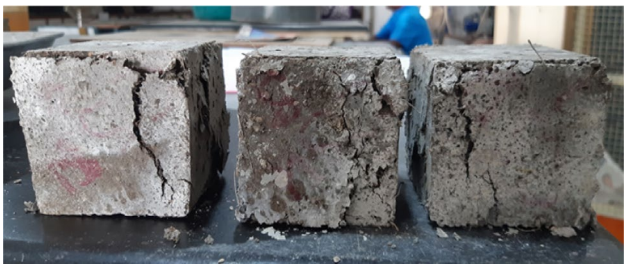

Fig. 6 Failure of CH used mortar cubes

Fig. 7 Failure of conventional mortar cubes

strength of 35 N/mm^2 both conventional materials used the mortar and CH used mortar. In the case of conventional materials used, the target strength was achieved while using the ratio 1:3. But, in the case of using CH, the ratio 1:3 gives only 17% of target strength, and hence, it is necessary to use different combinations of other admixtures, and it is done in this study.

In this study, it is not found any workability issues in the case of both conventional materials and CH used mortar with different combinations of other materials in all the trials and the slump values are found to be less than 50 mm except for some trials. The traditional way of increasing density from fresh concrete state to 3, 7, and 28 days was found in all the trial mixes. The same trends have been found in the case of compressive strength also. It can be noticeable that the density of the CSM3 (1:3) mix at 28 days is 2310 kg/m^3, and at the same time, the density of CCHM1 (1:3) mix at 28 days is only 1440 kg/m^3 which is approximately 38% lesser in comparison to CSM3 mix. Therefore, in the case of non-structural ferrocement elements where the strength is not the significant criteria, then this CCHM1 mix can be adopted so that the self-weight of that element could be reduced.

The failure of coconut husk used mortar cubes is ductile in nature compared to the brittle nature of the failure of conventional materials used mortar cubes. This ductile nature of the failure of CH used mortar mixes is an advantage in seismic zone areas. To show the success of this novel idea of using CH mortar in the production of ferrocement, it was tried and produced a ferrocement panel and can be considered as an innovative sustainable solution to the infrastructure development in ferrocement. This shows the possibility to use these ferrocement panels in field applications in the near future.

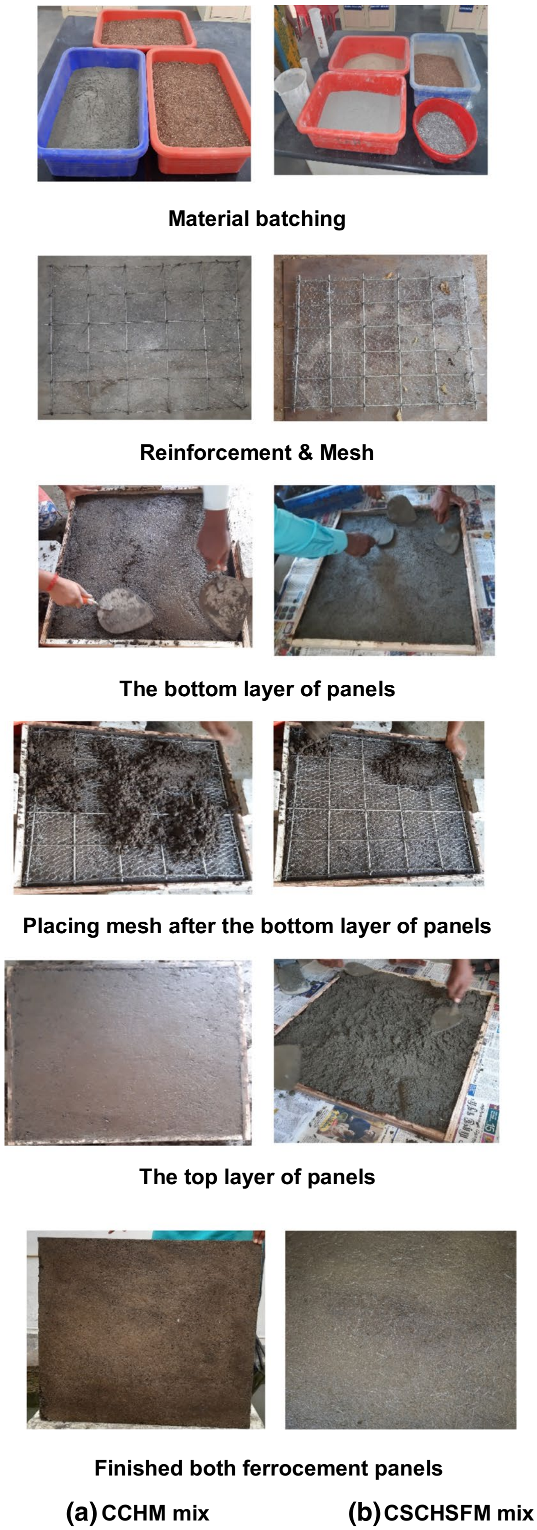

Fig. 8 Process pictures of ferrocement panels

Declarations

Conflict of interest Authors declare that there is no conflict of interest on this study and this manuscript as well.

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