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Case study

Performance of sustainable mortar using calcined clay, fly ash, limestone powder and reinforced with hybrid fibers

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A R T I C L E I N F O

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A B S T R A C T

Green mortar (GM) is a mortar that at least one of its components uses waste materials or materials that do not cause environmental destruction throughout their production. This research aims to design a mortar with the highest possible cement and sand substitutions with acceptable fresh and hardened properties. The experimental work was conduct in three phases. In phase one, calcined clay replaced cement by 20%, 25%, 30%, 35%, and 40% in mortar mixes. Then, the cement replacement raises to 50% by substituting cement with a combination of calcined clay (CC) and fly ash (FA) in different percentages in other mortar mixes. In phase two, limestone powder (LP) partially replaced sand by 20% and 30% (by weight) in two of the chosen mixes from phase one that contained high cement replacement and fairly good fresh and hardened properties. Then environmental impacts of GM mixes have been evaluated by estimating the reductions of CO_2 emissions from producing such mixes. Phase three involved the effects of incorporating 0.5% fibers (by volume) on the properties of GM using two types of steel fibers with different aspect ratios. Ultra steel fibers (USF) with an aspect ratio of 65 and steel nail fibers (SNF) with an aspect ratio of 20. The inclusion of hybrid fibers was by combining USF and SNF in different percentages while maintaining the same volumetric fraction of 0.5%. The fresh and hardened properties have been determined in phase three also. The results show that replacing OPC with 25% CC provides the best increment on compressive strength by increasing the compressive strength by about 21% at 28 days. The use of 20% LD as sand replacement increases the flow and 28 days-compressive strength by about 55% and 13%, respectively, for the mortar that contains 35% CC+ 15% FA. The test results of reinforced mixes show that the hybridization of 0.175% USF and 0.325% SNF affords the best enhancements on the mechanical properties. The results obtained from the estimated reduction of CO_2 emissions study reveal that incorporating 30% CC + 20% FA as cement replacements and 30% LP as a sand replacement reduces the CO_2 emissions by approximately 41%. Therefore, adopting the concept of green mortar is a promising approach for mitigating CO_2 emissions and preserving natural resources.

1. Introduction

"Going green" has become a top concern for our community in today's environment and sustainable engineering buildings. Such a concept should be considered as the core of this green revolution [1]. Green mortar (GM) is described as a mortar that uses solid waste

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materials as one or more of its ingredients. Also, it can possess the advantage that its manufacturing process does not result in ecological destruction. Furthermore, it has high performance and sustainability during the life cycle. Green mortar is also inexpensive to produce because waste materials are used as partial replacements for cement or aggregates. Continuously, disposal charges are eliminated, manufacturing power consumption is lower, and the durability is considerably greater. The replacement of traditional ingredients of mortar by waste materials and by-products gives an opportunity to manufacture economical and environment-friendly mortars [2,3].

Around eight percent of the overall carbon dioxide emissions in the world are generated from cement production activities. There are two main sources of cement manufacturing that generate CO_2 emissions. The first source is the chemical reaction associated with the production of the cement's main component, clinker, as carbonates (mostly limestone, $CaCO_3$) is decomposed by the presence of heat into oxides (mostly lime, CaO) and CO_2. The second source of CO_2 emissions is fossil fuel combustion to generate sufficient energy needed to heat the raw materials [4]. Carbon dioxide emissions remain harmful to the atmosphere and are a leading factor in the global climate change debate. The Intergovernmental Panel of Climate Change (IPCC) determines that emissions of carbon dioxide mostly compose the anthropic greenhouse gasses (GHG) (about 80% of greenhouse gases). Anthropic Carbon dioxide emissions trap the atmospheric heat, increase the global temperature that characterizes world climate change [5]. The most appropriate approach in the short-term to alleviate CO_2 releases of cement manufacturing involves reducing the cement content with increasing levels of SCMs [6].

The availability of traditional SCMs is low compared to cement demand, whereas common clays are widespread on the earth's crust. Calcined clays are the only other substances available in large enough quantities to maintain the trend of decreasing the cement content in blended cement mixtures [7]. Fly ash is one of the most widespread SCMs utilized in recent decades. Using fly ash as a partial substitution of cement decreases the volume of inpowderrial by-products that end up in landfills, thus causing air contamination. Besides increasing the greenness of the environment, fly ash improves durability, enhances workability, and reduces the heat of hydration of mortar and concrete [8]. River sand is the primary raw material for cement composites used as fine aggregate. The resources of natural river sand will not maintain forever. The natural resources are gradually dwindling, while the ecological system is unbalanced [9]. Over the past decades, the demand for aggregates to produce cement composites has remarkably grown in many countries. In order to mitigate the use of river sand and sea sand that can lead to the refraction of such materials, new strategies should be inspected and adopted [14]. On the other hand, limestone quarries generate large amounts of fine limestone powder during the crushing, cutting, and sewing processes of large limestone rocks. Such fine powders get piled up, and their existence is a big issue from aspects of disposal, pollution, and health hazards. The application of limestone powder as a substitute for sand provides promising opportunities for natural resources conservation, landfill disposals, and mortar production costs [10].

Mortars suffer from crack formation due to the shrinkage that occurs in their matrix. Proper solutions must be experienced to prevent the development of shrinkage strains, control cracks, and increase the tensile strength in an attempt to produce durable mortars [11].

Thus, this study aims to design GM with the highest possible level of substitution that satisfies fresh and mechanical properties. Such mortar has the structural requirements of masonry mortar. The measurable objectives are to:

1. Characterize the GM containing different percentages of calcined clay as partial substitutions of cement and binary substitution of cement by calcined clay and fly ash by physical and mechanical tests.
2. Determine the fresh, physical, and mechanical properties for GM prepared with suitable binary substitutions of cement and limestone powder as partial replacement of sand reinforced with mono and hybrid fibers.
3. Compare the ecological impacts of GM with plain mortar

2. Materials used

2.1. Cement

Commercially available (Type I) Ordinary Portland cement (OPC) provided by the Al-Mass cement factory was used in this research. The physical properties of the cement are shown in Table 1. The chemical composition of the cement is shown in Table 2. The physical and chemical test results show that the cement satisfies the requirements of Iraqi Standard Specification "IQS: 5/1984" [12].

Table 1
Physical properties of the OPC.

Physical properties	Results	Limits of IQS: 5/1984
Initial setting time (minute)	90	≥ 45 min
Final setting time (minute)	320	≤ 600 min
Fineness (Blain m^2/kg)	270	≥ 230 (m^2/kg)
Soundness by Autoclave Method (%)	0.02	Not more than 0.8
Compressive strength (MPa)		
3 days	17	≥ 15
7 days	26	≥ 23

Table 2
Chemical composition of the OPC.

Composition	Abbreviation	Percentage by weight	Limits of IQS: 5/1984
Lime	CaO	62.8	–
Silica	SiO_2	22.01	–
Alumina	Al_2O_3	5.67	–
Iron Oxide	Fe_2O_3	3.6	–
Sulfate	SO_3	2.46	$\leq$ 2.8
Magnesia	MgO	2.93	$\leq$ 5.0
Loss on ignition	L.O.I	2.19	$\leq$ 4.0
Insoluble Residue	I.R	0.91	$\leq$ 1.5
Lime saturation factor,%	L.S.F	86	66–102
Main Compounds (bogue's equation)			
Tri calcium Silicate	C_3S	38.08	–
Di calcium Silicate	C_2S	32.92	–
Tri calcium Aluminate	C_3A	8.93	–
Tetra calcium Aluminate-Ferrite	C_4AF	10.94	–

2.2. Sand

River sand supplied from the Khazer region (East of Mosul) was utilized in this research as fine aggregate. The specific gravity of the sand was 2.64, unit weight was 1670 kg/m^3, and the fineness modulus was 2.9.

2.3. Tap water

Ordinary tap water used for both mixing and the normal curing operations.

2.4. Calcined clay

Natural reddish brown clay was brought from the Al-Arabi region located in the North of Mosul city in Nineveh province. The size of the calcined clay grain used in the research was about 45 μm, the specific surface area was 495 m^2/kg, and the specific gravity was 2.46. The desired calcined clay used in the research was obtained, activated, and characterized by the following processes:

2.4.1. Selection of the clay deposit

Clay deposit selection relied on the geological properties and the reactivity potential of deposits. The fundamental requirements were the clay's preliminary identification based on previous reports and adequate resource availability. Consequently, the chosen clay deposit was at the worksite of Diwan Residential Compound located in the Al-Arabi region due to the previous soil investigations reports and the availability of sufficient amounts of clay. Moreover, massive excavation works are carried out daily during the project operations, as shown in Fig. 1.

2.4.2. Crushing process

The size of the raw clay collected from the deposit was approximately 100–150 mm, as shown in Fig. 2(a). The clay was crushed manually to smaller pieces with sizes between 10 and 30 mm, to ensure fluent access into the grinder's hopper.

Fig. 1. View of clay deposit at Al-Arabi region.

(a) Raw clay samples, (b) Grinding machine.

Fig. 2. (a) Raw clay samples, (b) Grinding machine.

2.4.3. Drying process

The drying operation of the crushed clay was carried out by a laboratory oven with a temperature of 100° C for 24 h to release the absorbed water between the clay particles. This step facilitates the following grinding operations and prevents the interference of the hydration water during the later calcination process [13].

2.4.4. Grinding process

The dried clay was ground by a commercial grinding machine type Guyixuan 150, illustrated in Fig. 2(b). Until the clay particle size reduces to about 0.1 mm, and 100% of the produced powder passes through the 0.15 mm sieve (sieve # 100) to ensure a homogenous heat diffusion in clay particles during the further calcination process [14].

2.4.5. Assessment of optimum calcination temperature

The determination of the optimum calcination temperature was by carrying out the strength activity index (SAI) test. This technique is the most suitable approach to identify the possible influence of mineral admixtures on the mechanical performance of mortars. The clay samples were exposed to heat to certain temperatures between 700 and 850°C with 50°C intervals. This is because of the predicted high clay activity in this temperature range. The duration of the calcining process was set to 60 min for all the samples [15]. The calcined clay obtained from each calcination temperature was used to prepare mortar specimens by substituting cement with 20%

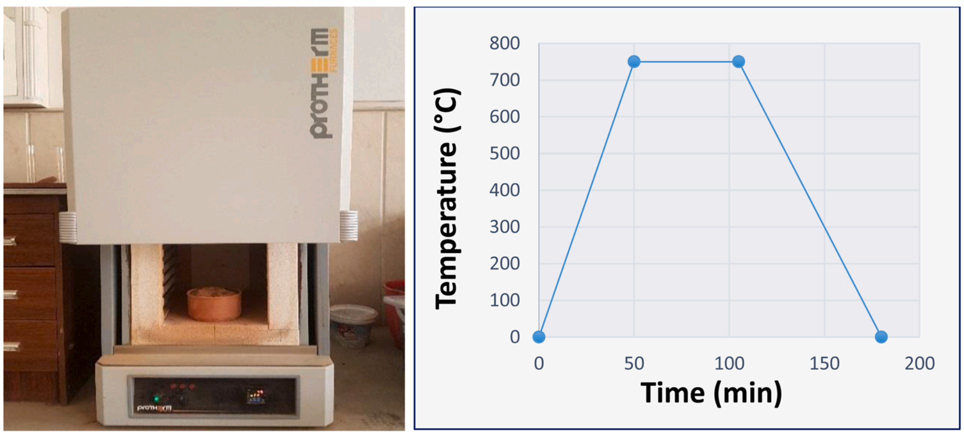

Fig. 3. (a) Laboratory furnace (b) Heating regime.

Fig. 4. Laboratory ball mill.

Table 3
Physical properties of the calcined clay.

Physical properties	Calcined clay	Pozzolan class N ASTM C618
Pozzolanic activity index with (OPC) at 28 days	117%	≥ 75%
Water requirements with control	105%	≤ 115%
Autoclave expansion or contraction	0.06%	0.8%
Specific gravity	2.46	–
Specific surface area m^2/g	495	–

of calcined clay. The compressive strength was determined at 7 and 28 days according to ASTM C109/C 109 M [16]. The optimum calcining temperature was 750°C according to the SAI results.

2.4.6. Clay calcination process

The clay calcination was by heating the clay with a programmable laboratory furnace type Prothern 442 T shown in Fig. 3(a), adopting the permanent bed technique. The temperature of the furnace that contained the clay raised from the room temperature to 750°C with a constant heating rate of 15°C/min maintaining the specific temperature for one hour. Then the furnace temperature was reduced to room temperature. As shown in Fig. 3(b).

2.4.7. Final grinding process

After completing the calcination process, the cooled calcined clay was exposed to additional grinding in a laboratory ball mill type Tencan Qm-4 illustrated in Fig. 4. The jar of the mill was filled by adding the calcined clay particles to the equipped multi-sized steel balls. Then the jar rotated for 30 min. The clay grains were crushed because of the impact action of the steel balls and the friction action of the clay's rolling. The purpose of this step is to increase the fineness of clay until the grain size becomes less than 45 μm and approximately 80% of the clay can pass through sieve # 325, to ensure sufficient reactivity during the hydration process [17]. This process is necessary to avoid the negative effect of grain size enlargement that may occur during the calcination process due to the sintering phenomenon of some clay minerals [18].

2.4.8. Calcined clay characterization

The physical properties of the produced calcined clay were characterized through several tests. The clay used in this research meets the requirements of natural pozzolan type N according to the standards of ASTM C618 [19]. The physical properties are listed in Table 3. The chemical composition of the produced calcined clay which also satisfies the requirements of natural pozzolan type N are listed in Table 4.

Table 4
Chemical composition of the calcined clay.

Oxides	Content % (by mass)	Pozzolan class N ASTM C618
CaO	15.01	–
SiO_2	46.01	–
Al_2O_3	21.06	–
Fe_2O_3	8.92	–
MgO	4.89	–
SO_3	0.3	≤ 4%
Na_2O	0.2	–
L.O.I	4.74	≤ 10%
$SiO_2+Al_2O_3+Fe_2O_3$	74.99	≥ 70%

Table 5
Physical properties of the fly ash.

Physical properties	Fly ash	Pozzolan class N ASTM C618
Pozzolanic activity index with(OPC) at 28 days	78%	≥ 75%
Water requirements with control	96%	≤ 115%
Autoclave expansion or contraction	0.02%	≤ 0.8%
Specific gravity	2.24	–
Specific surface area m^2/g	416	–

Table 6
Chemical composition of the fly ash.

Oxides	Content % (by mass)	Pozzolan class N ASTM C618
CaO	2.57	–
SiO_2	65	–
Al_2O_3	22.77	–
Fe_2O_3	6.25	–
MgO	3.05	–
SO_3	0.36	≤ 4%
L.O.I	0.00	≤ 10%
$SiO_2+Al_2O_3+Fe_2O_3$	94.02	≥ 70%

2.5. *Fly ash*

The fly ash type F (low calcium) was used in this work. The percentage of the fly ash particles passing through the 45 μm (sieve # 325) was 82%. Physical properties and chemical composition meet the requirements of natural pozzolan type N according to the standards of ASTM C618 [19]. The physical properties and the chemical composition are shown in Table 5 and Table 6, respectively.

2.6. *Limestone powder*

Limestone powder gathered from a local quarry in the Bashika region East of Mosul city was utilized as a partial replacement of sand. The limestone powder was generated in the quarry during the mining and cutting processes. The size of the obtained limestone powder was between 75 and 150 μm. The physical and properties are listed in Table 7. The chemical properties are listed in Table 8.

2.7. *Superplasticizer*

High range water reducing admixture type ViscoCrete®– 5930 superplasticizer produced by Sika Company for admixtures was used to control the desired workability as shown in Table 9. This chemical admixture is primarily composed of polycarboxylate and meets the superplasticizer Type F and G requirements according to ASTM C494 [20].

2.8. *Ultra-steel fibers*

Steel fibers type Dramix® ultra-steel fibers produced by Bekaert Company for steel wires were used to reinforce the green mortar. The straight shaped fibers are coated with a thin layer of brass, as shown in Fig. 5(a). The fibers were 13 mm long with a diameter of 0.2 mm and meets the requirements of ASTM A820/A820M [21]. The properties of the fibers are list in Table 10.

2.9. *Steel nail fibers*

Galvanized steel nails available in the local market produced by Pouyan Company for metal inpowderries were used as a fiber reinforcement for the green mortar. The steel fibers were straight-shaped with a one end button and a round cross-section, as shown in Fig. 5(b). The length of the fiber was 25 mm, and the diameter was 1.25 mm. The fibers comply with the ASTM A820/A820M [21]. The properties of the steel fibers are list in Table 11.

Table 7
Physical properties of the limestone powder.

Physical property	Result
Specific gravity	2.92
Blain Fineness (m^2/kg)	124
Unit weight (m^2/kg)	1530
Water absorption (%)	2.3

Table 8
Chemical composition of the limestone powder.

Elements	Content % (by mass)
Cao	46.5
SiO_2	4.15
Al_2O_3	1.3
Fe_2O_3	1.19
MgO	2.2
SO_3	0.66
K_2O	0.4
Na_2O	0.18
L.O.I	42.68

Table 9
Technical data of ViscoCrete® −5930.

Basis	Modified polycarboxylate aqueous solution
Density	Approximately 1.080 kg/liter
Dosage	0.8–2.0% of cement by weight
pH	8.0 ± 1.0
Chloride Content	Nil


(a) Ultra-steel fibers (b) Steel nail fibers.

Fig. 5. (a) Ultra-steel fibers (b) Steel nail fibers.

Table 10
Properties of the ultra-steel fibers.

Property	Specifications
Density	7840 kg/m^3
Tensile strength	2850 MPa
Shape	Straight
Color	Yellow
Length (L)	13 mm
Diameter (D)	0.2 mm
Aspect ratio (L/D)	65

Table 11
Properties of the steel nail fibers*.

Property	Specifications
Density	7145 kg/m^3
Tensile strength	2250 MPa
Shape	Straight with one end button
Color	Gray
Length (L)	25 mm
Diameter (D)	1.25 mm
Aspect ratio (L/D)	20

3. Experimental program

3.1. Mix proportions

In this study 17 mortar mixes were prepared in addition to the control mix (MO). The mix proportion for all the mixes was 1:3 (cement: sand) using a constant water/binder (w/b) ratio of 0.48. The sand was in a surface saturated dry condition in all mixes. The amount of superplasticizer (SP) varied from 0.8% to 2% by the weight of the binder. The mixes were divided into three main groups.

The first group consists of eight mixes. The cement was replaced with calcined clay (by weight) in amounts of 20%, 25%, 30%, 35%, and 40% in M1-M5 mixes, respectively. Then the amount of cement replacement was raised to 50% through substituting the cement with a combination of calcined clay (CC) and fly ash (FA) in different amounts, such as 40% CC + 10% FA, 35% CC + 15% FA, and 30% CC+ 20% FA in M6, M7, and M8 mixes, respectively, as illustrated in Table 12.

The second group consists of four mixes. The limestone powder (LD) replaced the sand partially. With a fixed amount of superplasticizer of 1.8% of the binder (by weight) and a fixed water/binder (w/b) of 0.48. Regarding the mix M7 (35% CC+ 15% FA), the LD replaced the sand by 20% and 30% (by weight) to represent the mixes ML1 and ML2, respectively. Regarding the mix M8 (30% CC+ 20% FA), the LD replaced sand by 20% and 30% (by weight) to represent the mixes ML2 and ML4, respectively, as shown in Table 13. The third group consists of 5 mixes in addition to the suggested control mix. The control determination was according to the results of the carried out tests on the second group. Steel fibers were added by 0.5% (by volume) to the third group mixes. The amount of superplasticizer was then raised to 2.0% of the binder to maintain appropriate workability. The mix ML1 was considered the control mix MF0 for this group (ML1 =MF0). The ultra-steel fibers (USF) and steel nail fibers (SNF) have been added individually in MF1 and MF2 mixes, respectively. Then hybrid fibers were added by combining the two types of fibers in different percentages, maintaining the same volumetric fraction of 0.5%. The amounts of the hybridization were; 50% USF+ 50% SNF, 65% USF+ 35% SNF, and 35% USF+ 65% SNF in MF3, MF4, and MF5 mixes, respectively, as shown in Table 14.

3.2. Mixing procedure

The mixing procedure was carried out by blending the cement, calcined clay, fly ash, and sand manually according to the suggested mix proportions for 3 min to ensure homogeneity of the blend. The superplasticizer was then added to the mixing water and stirred following the instructions of the manufacturer. Then the water and the superplasticizer have been added to the blend for another 3 min. The addition of the fibers was done by uniformly spreading the fibers during the mixing procedure to guarantee that the fibers were uniformly distributed throughout the mix. The total duration for mixing all the constituents was 6 min. The ingredients of the green mortar are shown in Fig. 6.

3.3. Casting and curing procedures

After completing the mixing procedure flow test was carried out before casting to determine the workability for each mix. The fresh mortar was then cast into the specified molds in two equal layers. Each layer was compact by using a vibrating table for 30 s. The first and second groups of mixes consist of 13 mixes. Nine cubes of 50 × 50 × 50 mm for each mix were cast for the compression test, using three cubes for each age (7, 28, and 90 days). Six prisms of 40 × 40 × 160 mm were then cast for the flexural test at 28 and 90 days. Four cylinders of 100 × 200 mm were also cast for the splitting tensile test. Three cubes of 70 × 70 × 70 mm were then cast for the ultrasonic pulse velocity, water absorption, bulk dry density tests at 28 and 90 days. For the specimens which contained steel fibers. Nine cubes of 50 × 50 × 50 mm were cast for the compression test, using three cubes for each age (7, 28, and 28 days). Nine prisms of 40 × 40 × 160 mm were also cast for the flexural strength, flexural toughness, and shrinkage test. Four cylinders of 100 × 200 mm were cast finally for the splitting tensile and static modulus of elasticity tests. The samples which contained steel fibers are illustrated in Fig. 7.

Then the face of the cast sample was leveled by a trowel. The specimens were demolded after 24 h and placed into a tab water tank for curing, as shown in Fig. 8. The temperature of the curing water was 23 ± 2°C according to the standards of ASTM C192 [22].

Table 12
Mix proportions for cement replacement mixes.

Index	Cement (kg/m^3)	CC (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	SP (%)	Sand (kg/m^3)	w/b
M0	507	0	0	243	0.8	1521	0.48
M1	406	101	0	243	1.0	1521	0.48
M2	380	127	0	243	1.2	1521	0.48
M3	355	152	0	243	1.4	1521	0.48
M4	330	177	0	243	1.6	1521	0.48
M5	304	203	0	243	1.8	1521	0.48
M6	254	203	50	243	1.8	1521	0.48
M7	254	177	76	243	1.8	1521	0.48
M8	254	152	101	243	1.8	1521	0.48

Table 13
Mix proportions for sand replacement mixes.

Index	Cement (kg/m^3)	CC (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	LP (kg/m^3)	SP (%)	w/b
ML1	254	177	76	1217	304	1.8	0.48
ML2	254	152	101	1217	304	1.8	0.48
ML3	254	177	76	1065	456	1.8	0.48
ML4	254	152	101	1065	456	1.8	0.48

Table 14
Mix proportions for steel fibers mixes.

Index	Cement kg/m^3	CC kg/m^3	FA kg/m^3	Sand kg/m^3	LP kg/m^3	USF (%)	SNF (%)
MF0	254	177	76	1217	304	–	–
MF1	254	177	76	1217	304	0.5	–
MF2	254	177	76	1217	304	–	0.5
MF4	254	177	76	1217	304	0. 25	0.25
MF4	254	177	76	1217	304	0.325	0.175
MF5	254	177	76	1217	304	0.175	0.325

Fig. 6. Ingredients of the produced green mortar.

3.4. Test procedure

The flow test is to determine the flow (workability) of hydraulic cement mortars and cementitious materials mortars, as stated in the standards of ASTM C1437 [23]. The flow table and the conical mold used in this test satisfy the specifications stated in ASTM C230 [24]. The compressive strength of the mortar samples was carried out according to ASTM C109/C 109 M [16]. Test cube specimens of 50 × 50 × 50 mm were used in this test, and the average strength of three cubes for each test age at 7, 28, and 90 days is adopted. The splitting tensile strength of the mortar specimens was carried out according to the ASTM C496 [25]. Cylinder specimens of 100 × 200 mm were utilized in this test. Test prisms of 40 × 40 × 160 mm were utilized for the flexural strength of mortars adopting the center point loading method according to ASTM C348 [26]. The water absorption of the mortar was conducted according to the ASTM C642 [27]. Test cubes specimens of 70 × 70 × 70 mm were utilized in this test. Cube specimens of 70 × 70 × 70 mm were utilized in this test. The specimens were tested in an air-dried condition. Three specimens for each mix were tested, and the average result of the three readings was adopted. This non-destructive test was conducted according to the ASTM C597 [28]. Cylindrical specimens of 100 × 200 mm were utilized to determine the static modulus of elasticity according to ASTM C469 [29]. The flexural toughness test for the mortar was conducted according to ASTM C1018 [30]. Prism specimens of 40 × 40 × 160 mm were used in this test at the age of 90 days. The drying shrinkage test was carried out on prism specimens for mortar mixes that contain mono and hybrid reinforcement. The test was performed according to the standards of ASTM C157/C 157 M-99 [31].

4. Results and discussions

4.1. Fresh and hardened properties of green mortar

4.1.1. Flowability

The flowability for mortar mixes which contained partial cement replacement with calcined clay and (calcined clay + fly ash) are presented in Table 15.

Fig. 7. Reinforced mortar specimens.

Fig. 8. Curing of the specimens.

Table 15
Flow test results for cement replacement mixes.

Index	Cement (%)	Calcined clay (%)	Fly ash (%)	SP (%)	w/b	Flow (%)
M0	100	0	0	0.8	0.48	105
M1	80	20	0	1	0.48	105
M2	75	25	0	1.2	0.48	85
M3	70	30	0	1.4	0.48	45
M4	65	35	0	1.6	0.48	20
M5	60	40	0	1.8	0.48	0
M6	50	40	10	1.8	0.48	30
M7	50	35	15	1.8	0.48	55
M8	50	30	20	1.8	0.48	80

Initial studies have shown that the presence of calcined clay increases the water demand for fresh mortar mixes [32]. Recent researches have revealed that the high water demand in mortar mixes that contain calcined clay is due to the high fineness and narrow size distribution of the calcined clay [33]. The most suitable approach to overcome the high water demand issue in fresh mortar mixes is by adding high range water reducers (superplasticizers) to the cement blends [34]. Among various types of superplasticizers, researchers have proved that the polycarboxylate based superplasticizers are the most effective water reducers on binders that contain calcined clay [35]. Therefore ViscoCrete®− 5930 superplasticizer which is primarily composed of polycarboxylate was used in this research. According to the recommendations in the ViscoCrete®− 5930 technical data, the allowable dosage should be (0.8–2.0) % of the binder by weight. To reach the ideal flowability of 105% in the control mix (M0), 0.8% of superplasticizer was required.

For these reasons and considering the high water demand of calcined clay, the superplasticizer dosage increased from 1% to 1.8% as the amount of calcined clay replacement was increased in M1-M5 mixes.

The obtained results showed that the flow in calcined clay mixes was decreased from 105% in M1 mix to 85%, 45%, 20% and 0% in M2, M3, M4 and M5 mixes. This could be attributed to the relatively high fineness of the utilized calcined clay (495 m^2/kg) when compared to the fineness of the utilized cement (290 m^2/kg). Therefore it was not possible to increase the amount of calcined clay by more than 40%. To increase the level of cement substitution to 50% with an acceptable flow, new mixes containing calcined clay and fly ash were proposed as in M6, M7 and M8 mixes. The addition of fly ash was based on the fact that utilizing fly ash as a supplementary cementitious material enhances the workability of fresh mortars and produces greener materials [36]. This is due to the smooth surface and spherical shape of fly ash grains [37], therefore fly ash was added in amounts of 10%, 15% and 20% to M5, M4 and M3 mixes to represent the mixes M6, M7 and M8, respectively, with a fixed superplasticizer dosage of 1.8%, while the amount of the cement was 50% of the binder materials for the said three mixes. The flow test results showed that there was an obvious improvement in the flow performance of the fresh green mortar when fly ash was added to the blend. The flow increased from 0%, 20% and 45–25%, 55% and 80% in M6, M7 and M8 mixes, respectively. This could be attributed to the sliding effect on the fresh mortar constituents due to the smooth surface and spherical shape of fly ash grains [38].

The flow test results for green mortar mixes which contained limestone powder (LD) as a partial replacement of normal sand are presented in Table 16. Previous researches have proven that utilizing limestone powder in certain percentages as fine aggregate improves the flow performance of fresh mortar and concrete mixes. Besides, the environmental advantage from consuming waste materials [39]. According to the obtained flow test results for the first 8 mixes and considering that the main goal in this research was to achieve higher levels of cement substitutions, the limestone powder replacement was experienced on M7 and M8 mixes. However, the M6 mix was not considered for further mixes preparations because of its relatively low flow. The dosage of superplasticizer was fixed to 1.8% by weight of the binder. Normal sand was replaced by limestone powder by 20% and 30% in M7 and M8 mixes respectively, representing ML1, ML2, ML3, and ML4 mixes.

The flow test results showed that partially replacing sand with limestone powder increased the flowability for all green mortar mixes. This can be attributed to the generated filler effect caused by the limestone powder, where limestone powder replaced the water in voids between the sand particles resulting in higher availability of water for lubrication [40]. Consequently, the flow in the M7 mix was increased from 55% to 85% in ML1 mix and 70% in ML3 mix, and also increased in M8 mix from 80% to 105% in ML2 and 95% in ML4 mix. Although both 20% and 30% of limestone powder enhanced the workability, but the flow with 20% of limestone powder was significantly higher and the mortar seems to lose its workability as the amount of limestone powder was increased. This can be attributed to the fact that the high content of limestone powder increased the fineness of the total fine aggregate, therefore more water is required to lubricate the particles [41].

Individual and hybrid steel fibers were used in this research, due to its positive influence on mechanical properties such as tensile strength, flexural strength, and flexural toughness [42]. Initial studies have revealed that the inclusion of fibers to cement composites generally reduces the workability of fresh mortars, due to the creation of a denser skeleton which affects the internal flow motion and rheological properties of the fresh mortar mix [42]. Other studies on various types of fibers proved that steel fibers have a lower water demand than polymer and natural fibers [43]. Many studies proved that the incorporation of superplasticizers is the most efficient technique to maintain the fresh mortar's workability [44]. For these reasons and considering the maximum allowable dosage for the utilized superplasticizer, the amount of superplasticizer was raised from 1.8% to 2.0% of the binder by weight with a fixed w/b of 0.48 for all mixes reinforced by a volumetric fraction of 0.5% with ultra-steel fibers (USF) and steel nail fibers (SNF) individually and dually. According to the obtained flow results and the compression test results at 7 and 28 days on the prior mixes, the mix ML1 was

Table 16
Flow test results for sand replacement mixes.

Index	Cement (%)	CC (%)	FA (%)	SP (%)	Fine aggregate		w/b	Flow (%)
					Sand (%)	LD (%)		
ML1	50	35	15	1.8	80	20	0.48	85
ML2	50	30	20	1.8	80	20	0.48	105
ML3	50	35	15	1.8	70	30	0.48	70
ML4	50	30	20	1.8	70	30	0.48	95

Table 17
Flow test results for reinforced green mortar mixes.

Mix	Cement (%)	CC (%)	FA (%)	Fine aggregate		SP (%)	Fibers		Flow (%)
				Sand (%)	LD (%)		USF (%)	SNF (%)	
MF0	50	35	15	80	20	1.8	–	–	85
MF1	50	35	15	80	20	2.0	0.5	–	85
MF2	50	35	15	80	20	2.0	–	0.5	85
MF3	50	35	15	80	20	2.0	0.25	0.25	85
MF4	50	35	15	80	20	2.0	0.325	0.175	85
MF5	50	35	15	80	20	2.0	0.175	0.325	85

considered the control mix for reinforced mortar mixes (ML1 = MF0). Table 17 illustrates the flow test results for all reinforced mortar mixes.

The flow test results indicate that flowabilty for all reinforced mixes was the same and the small reduction in flow due to the low volumetric fraction and type of fibers was balanced by the addition of the superplasticizer. The obtained results are supported by other researchers when the same volumetric fraction of steel fibers were added to green mortar mixes [45].

4.1.2. Compressive strength

The compression test results at 7, 28 and 90 days, for green mortar mixes which are comprised of different percentages of calcined clay and fly ash as cement replacements are presented in Table 18 and Fig. 9.

The compression test results indicated that partially replacing cement with calcined clay generally increases the compressive strength of mortars. The results showed that the compressive strength at 90 days when cement was replaced with calcined clay by 20%, 25% and 30% increased by 10%, 20%, and 3% in M1, M2 and M3 mixes, respectively. This can be attributed to the chemical composition of the calcined clay and the amorphous phases that are formed during the clay calcination process. According to these aspects, silicon and aluminum can react with calcium hydroxide and water to form calcium silicate hydrates (C-S-H) and calcium aluminate silicate hydrates (C-A-S-H). These extra phases can contribute in the mortar's compressive strength [46]. The compressive strength at 90 days when calcined clay replaced cement by 35% and 40% was reduced by 13% and 24% in M4 and M5 mixes, respectively, as shown in Fig 4.4. This can be attributed to the relatively slow pozzolanic reaction between the calcined clay reactive constituents and the excess of calcium hydroxide formed during the hydration, where previous studies estimated that 20% of the pozzolanic reaction occurs in 90 days, while 80% of the cement reactions occur in 90 days [46,47]. The relation between the percentages of calcined clay replacement and the compression strength at 90 days are shown in Fig. 10.

The compressive strength results at 90 days for green mortar mixes which contained 50% cement replacement was reduced by 22%, 30% and 40% in M6, M7 and M8 mixes, respectively. This can be attributed to the fact that higher cement replacement results in decreasing the available belite (C_2S) and alite (C_3S) phases, which are the fundamental reactive elements of the cement composite [48]. The compressive strength for the M6 mix which contained 40% of calcined clay with the addition of 10% fly ash was higher at all ages than the compressive strength for the M5 mix which contained only 40% of calcined clay. This can be attributed to the additional hydrate products that were generated due to the fly ash's dissolved ions of silica and aluminum reacted with the calcium that exist in the calcium hydroxide [49]. On the other hand, the compressive strength in mix M7 (35% CC+15% FA) was higher than compressive strength in mix M8 (30% CC + 20% FA). The compression strength at 90 days was reduced by 30% and 40% in M7 and M8 mixes, respectively. This phenomenon is attributed to the differences in physical structure alterations that occur in both calcined clay and fly ash binders. The capillary pore space is decreased to a critical size (10–30 nm) which leads to the densification of microstructure. The calcined clay binding matrix reaches the critical pore size earlier than fly ash binding matrix, hence the contribution in strength of calcined clay is higher than fly ash [50].

The compressive strength at 7, 28 and 90 days for green mortar mixes which contain limestone powder (LD) as a partial replacement of sand are shown in Table 19. Limestone powder replaced normal sand in M7 and M8 mixes. The selection of these two mixes was based on the obtained flow results. For the M7 mix, LD substituted sand by 20% and 30% to represent ML1 and ML3 mixes

Table 18
Compressive strength for green mortar mixes.

Index	Cement (%)	Calcined clay (%)	Fly ash (%)	Compressive strength (MPa)		
				7 days	28 days	90 days
M0	100	0	0	29	38	50.8
M1	80	20	0	38.5	42.7	55.8
M2	75	25	0	39.8	45.8	60.8
M3	70	30	0	34.4	41.6	52.3
M4	65	35	0	30.2	36.2	44.3
M5	60	40	0	25.5	29.3	38.7
M6	50	40	10	27.6	30.9	39.5
M7	50	35	15	22.7	28.2	35.5
M8	50	30	20	20	23	30.4

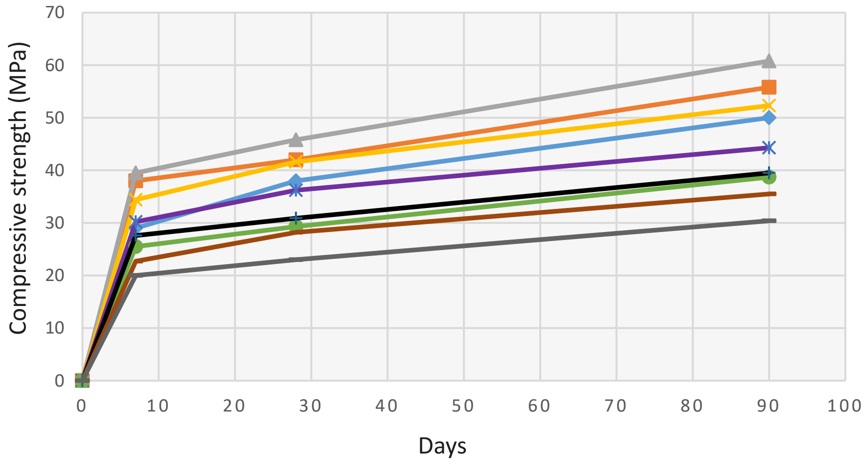

Fig. 9. Compressive strength development for cement replacement mixes.

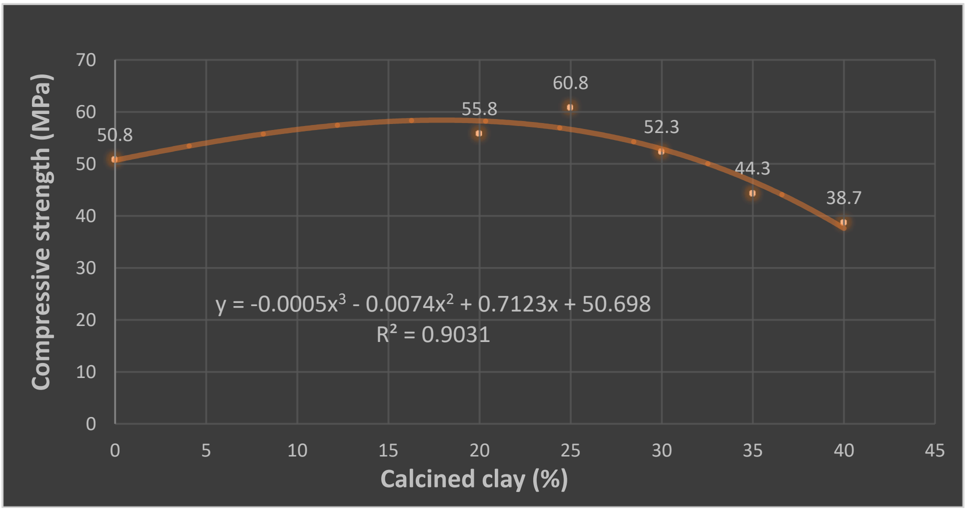

Fig. 10. Calcined clay percentages and compressive strength relation.

Table 19
Compressive strength for green mortar sand replacement mixes.

Index	C (%)	CC (%)	FA (%)	Fine aggregate		Compressive strength (MPa)		
				Sand (%)	LD (%)	7 days	28 days	90 days
ML1	50	35	15	80	20	26.4	35.5	40.2
ML2	50	30	20	80	20	23	25.8	33.8
ML3	50	35	15	70	30	24.7	29.9	37.3
ML4	50	30	20	70	30	21.4	24.1	31.3

respectively. For the M8, mix LD also substituted sand by 20% and 30% to represent ML2 and ML4 mixes respectively.

The improvement in compression strength for (ML1, ML3) and (ML2, ML4) in comparison with M7and M8 mixes, respectively, are demonstrated in Fig. 12. From the obtained results at 7, 28 and 90 days, it can be noticed that the compressive strength was increased in ML1 mix by 16%, 13%, and 13%. Also increases were also recorded in ML3 mix by 8%, 6%, and 5% when compared to the M7 mix. Consequently, the compressive strength at the same ages was increased in ML2 mix by 15%, 12% and 11%. The increases have also been seen in ML4 mix by 7%, 5% and 3% when compared to the M8 mix. The increment in the compressive strength is related to the void filling effect of limestone powder particles, which filled the pore structure of the mortar, resulting in the improvement of the compressive strength [51]. On the other hand, the increment in the compressive strength when 20% of LD replaced sand was higher than the increment of strength when 30% of LD was replaced. The reason for this behavior is that excess amounts of LD can raise the

Table 20
Compressive strength for reinforced green mortar mixes.

Index	Fibers (%)		Compressive strength (MPa)		
	USF	SNF	7 days	28 days	90 days
MF0	–	–	26.4	35.5	40.2
MF1	0.5	–	26.9	36.8	41
MF2	–	0.5	27.7	37.6	42.2
MF3	0.25	0.25	28.5	38.7	43.5
MF4	0.325	0.175	27.2	37	41.5
MF5	0.175	0.325	30.4	41.2	45.8

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Fig. 11. Relative compressive strength for reinforced mixes at 90 days.

specific surface area of the total fine aggregates. The increment in the surface area of aggregates will require more binding materials. As the amount of binding materials was the same, the strength with 30% of LD replacement was reduced when compared to 20% of LD replacement, hence more binding materials was needed to envelope the fine aggregates [52]. The obtained results also showed that the effect of limestone is reduced with age in the four mixes, which is probably because of the dilution effect of LD fine particles [53].

The results of the compressive strength test for green mortar mixes that contain mono and hybrid reinforcement are shown in Table 20.

According to the obtained results in the previous stage, the mix ML1 has been adopted as the control mix in this stage (ML1 = MF0). The binder material was composed of 50% cement, 35% calcined clay, and 15% fly ash, whereas the fine aggregate was composed of 80% normal sand and 20% limestone powder. Ultra-steel fibers (USF) with an aspect ratio of 65, and steel nail fibers (SNF) with an aspect ratio of 20.

The results of the compressive strength test for green mortar reinforced mixes revealed that the inclusion of 0.5% (by volume) of steel fibers, enhances the compressive strength. The increment in compressive strength was about 2–16% for the fiber reinforcement mixes at various ages when compared to the control mix (MF0). This is related to the improvement of the mechanical bond strength between the mortar matrix and the steel fibers, where fibers delay the formation of cracks and bridge the splitting cracks [23]. The obtained results also indicate that the increment in compressive strength when SNF fibers (20 mm long) were individually included in the MF2 mix was higher than the increment when USF fibers (13 mm long) were individually included in the MF1 mix. The compressive strength in the MF2 mix was increased by 5%, 6% and 5% at 7, 28 and 90 days, respectively, while the strength in MF1 was increased by 1%, 3% and 2% at the same ages. This can be attributed to that longer fibers possess higher pull-out properties and can efficiently control macro cracks propagation [54]. The results of hybrid steel fiber reinforcement show more significant improvements in compressive strength, especially in MF3 and MF5 mixes as shown in Fig. 11. For the MF3 mix, the compressive strength was increased by 8%, 9% and 8% at 7, 28 and 90 days, respectively. The best results were obtained in MF5 (0.175% USF, 0.325% SNF) mix, where the compressive strength was increased by 15%, 16% and 14% at 7, 28 and 90 days, respectively. This improvement is due to the synergic mechanism effect of the hybridization of two types of steel fibers with different sizes. The smaller size fibers bridged the micro-cracks and the larger size fibers arrested the macro-crack propagation [55].

4.1.2.1. Splitting tensile strength. The splitting tensile strength at 28 and 90 days for GM mixes which are comprised of different percentages of calcined clay and fly ash as cement replacement are presented in Table 21. The splitting tensile strength for GM mixes which contain limestone powder as a partial replacement of sand are represented in Table 22.

The results showed that the splitting tensile strength at 90 days when cement was replaced with calcined clay by 20%, 25% and 30% increased by 8%, 18% and 13% in M1, M2, and M3 mixes, respectively, as shown in Fig. 14. This is because additional hydrate products (C-S-H) and (C-A-S-H) which enhance the strength have been formed from the amorphous silica and alumina reaction with

Table 21
Splitting tensile strength for cement replacement mortar mixes.

Index	Cement (%)	CC (%)	FA (%)	Splitting tensile strength (MPa)	
				28 days	90 days
M0	100	0	0	2.65	3.13
M1	80	20	0	2.97	3.39
M2	75	25	0	3.04	3.68
M3	70	30	0	3.01	3.53
M4	65	35	0	2.68	3.11
M5	60	40	0	2.48	2.97
M6	50	40	10	2.14	2.4
M7	50	35	15	2.1	2.35
M8	50	30	20	2.07	2.25

Table 22
Splitting tensile strength for sand replacement mortar mixes.

Index	C (%)	CC (%)	FA (%)	Fine aggregate (%)		Splitting tensile strength (MPa)	
				Sand	LD	28 day	90 day
ML1	50	35	15	80	20	2.02	2.22
ML2	50	30	20	80	20	1.91	2.12
ML3	50	35	15	70	30	1.95	2.04
ML4	50	30	20	70	30	1.83	2.0

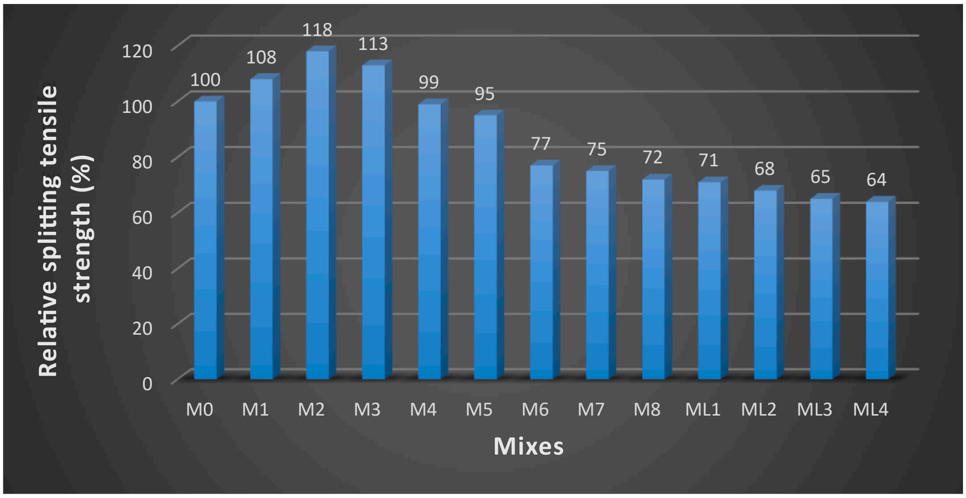

Fig. 12. Relative splitting tensile strength for GM mixes at 90 days.

the generated calcium hydroxide [56].

The obtained results also showed that the splitting tensile strength at 90 days, when calcined clay replaced cement by 35% and 40% was reduced by 1% and 5% in M4 and M5 mixes, respectively, as shown in Fig. 12. The reason for this reduction is that while the cement content is reduced, insufficient amounts of calcium hydroxide are generated to react the activated silica and alumina from the calcined clay, therefore the excessive silica and alumina amounts do not possess the cementitious property and the splitting tensile strength is reduced [57].

On the other hand, increasing the amount of cement replacement to 50% caused a significant reduction in the splitting tensile strength. The splitting tensile strength at 90days was reduced by 23%, 25% and 28% in M6, M7, and M8 mixes, respectively, when compared to the reference mix (M0) as shown in Fig 4.6. The reason for this reduction in strength is that a high level of cement substitution results in decreasing the main reactive elements such as C_3S and C_2S [58–61].

For GM mortar mixes which contained limestone powder (LD) as a partial substitution of normal sand, the results revealed that replacing normal sand with LD generally reduces the splitting tensile strength as shown in Table 4.8. From the obtained results at 28 and 90 days, it can be noticed that the splitting tensile strength was decreased in ML1 mix by 4%, and 6%, and was also decreased in ML3 mix by 8%, and 14% when compared to the M7 mix. Consequently, the splitting tensile strength at the same age was decreased in the ML2 mix by 8% and 6% and also decreased in the ML4 mix by 12% and 11% when compared to the M8 mix. This can be attributed to that the smooth surface and sharp edges of LD particles result in week bonding between the sand grains [62–64].

The splitting tensile strength test results for GM mixes reinforced with mono and hybrid fibers at 28 and 90 days, are shown in Table 23.

The splitting tensile strength results indicate that the inclusion of 0.5% (by volume) of fibers generally increases the mortar's splitting tensile strength. The increment at 28 and 90 days was about 10–26% for the different reinforced mortar mixes because the fibers improve the mortar's ability to transmit the tensile stresses beyond crack formation [65]. The obtained results also indicate that the increment in the splitting tensile stress when SNF fibers (straight with one end-button) were individually included in the MF2 mix was higher than the increment when USF fibers (straight shape) were individually included in the MF1 mix. The splitting tensile strength in the MF2 mix was increased by 17%, and 18% at 28 and 90 days, respectively, while the strength in MF1 was increased by 12%, and 10% at the same age as shown in Fig. 15. The difference of the effect on tensile stress between these two types can be happened because button-end fibers (SNF) offer a better failure attitude then straight fibers (USF), due to their better mechanical interlocking behavior [66]. The results of hybrid steel fiber reinforcement show higher improvement in splitting tensile strength, particularly in MF3 and MF5 mixes shown in Fig. 13. Concerning the MF3 (0.25% USF, 0.25% SNF) mix, the splitting tensile strength was increased by about 20% at 28 and 90 days. The best results were obtained in MF5 (0.175% USF, 0.325% SNF) mix, where the splitting tensile strength was increased by about 24% and 26% at 28 and 90 days, respectively. The better enhancement earned from

Table 23
Splitting tensile strength for reinforced GM mixes.

Index	Fibers (%)		Splitting tensile strength (MPa)	
	USF	SNF	28 days	90 days
MF0	–	–	2.02	2.22
MF1	0.5	–	2.26	2.44
MF2	–	0.5	2.38	2.62
MF3	0.25	0.25	2.42	2.66
MF4	0.325	0.175	2.32	2.57
MF5	0.175	0.325	2.51	2.79

the hybridization of two types with different sizes of fibers is because the tension in concrete and mortar is a multi-scaled process and each fiber size restricts the crack growth of its scale and has minor or no effects on other scale cracks [67].

4.1.2.2. Flexural tensile strength. The flexural tensile strength results at 28 and 90 days for GM mixes which are comprised of different percentages of calcined clay and fly ash as cement replacement are presented in Table 24. The results show that the highest flexural strength value was recorded when calcined clay replaced sand by 25%. The flexural strength at 90 days was increased by 21% in the M2 mix when compared to the M0 mix as shown in Fig. 14. This is related to the pozzolanic activity of the calcined clay [68].

The obtained results showed that replacing cement for more than 30% (M4-M8) mixes caused a reduction in flexural strength as illustrated in Fig. 16 due to the reduction in the formation of calcium hydroxide that promotes the pozzolanic reaction of supplementary cementitious materials [69].

The flexural strength for GM mixes which contain limestone powder as a partial replacement of sand is represented in Table 25. The results show that partially replacing normal sand by 20% and 30% with LD decreased the flexural strength. The flexural strength at 90 days was decreased by 7% in the ML1 mix and 16% in the ML3 mix when compared to the M7 mix. The flexural strength at 90 days was also decreased by 6% in the ML2 mix and 12% in the ML4 mix when compared to the M8 mix. The reason for this reduction is that the

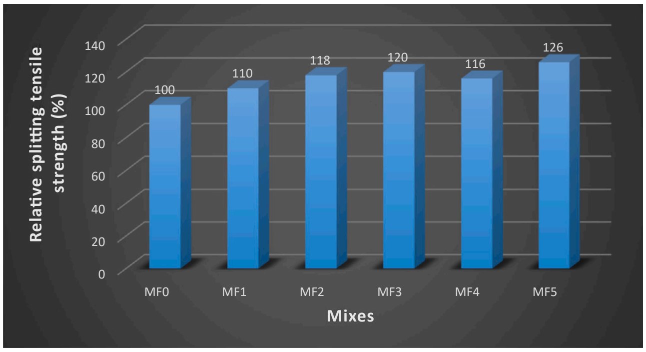

Fig. 13. Relative splitting tensile strength for reinforced GM at 90 days.

Table 24
Flexural strength for cement replacement mortar mixes.

Index	Cement (%)	CC (%)	FA (%)	Flexural strength (MPa)	
				28 days	90 days
M0	100	0	0	6.89	7.72
M1	80	20	0	7.83	8.92
M2	75	25	0	8.03	9.31
M3	70	30	0	8.55	9.23
M4	65	35	0	7.19	7.83
M5	60	40	0	6.61	7.26
M6	50	40	10	5.82	5.89
M7	50	35	15	5.52	6.13
M8	50	30	20	4.36	5.33

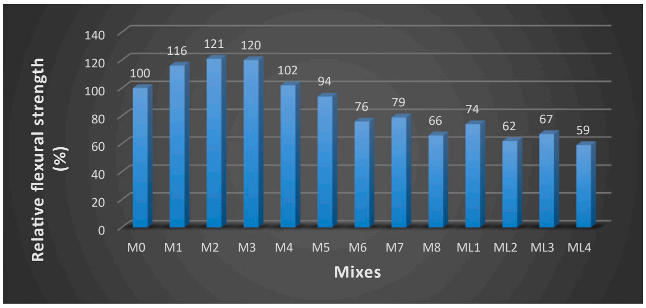

Fig. 14. Relative flexural strength for GM mixes at 90 days.

relatively smooth texture and high angularity of LD when compared to normal sand adversely affect the flexural strength [70].

The flexural strength for mono and hybrid reinforced GM mixes at 28 and 90 days are shown in Table 26.

The flexural strength results show that the inclusion of 0.5% (by volume) mono and hybrid steel fibers significantly increases the flexural strength as shown in Table 26. The increment at 28 and 90 days was about 8–34% for the different reinforced mortar mixes. The obtained results also indicate that the increment in the flexural stress when SNF fibers were individually added in the MF2 mix was higher than the increment when USF fibers were individually included in the MF1 mix. The flexural strength in the MF2 mix was increased by 17% and 23% at 28 and 90 days, respectively, while the strength in MF1 was increased by 8% and 15% at the same age as shown in Fig 4.9. This can be attributed to that SNF have better bonding performance with the surrounding matrix, due to its longer length and their anchorage mechanism [71]. The results of hybrid steel fiber reinforcement show higher improvement in flexural strength. The highest increment in flexural strength was noticed in MF5 (0.175% USF, 0.325% SNF) mix, where the flexural strength was increased by about 32% and 34% at 28 and 90 days, respectively. This is because hybrid fibers have a higher ability to restrain cracks than mono fibers [72]. The relative flexural strengths for reinforced green mortar mixes at 90 days compared with the reference mix (M0) are shown in Fig. 15.

4.1.2.3. Bulk dry density. The Bulk dry density at 28 and 90 days for cement replacement mixes are presented in Table 27. The bulk density values for sand replacement mixes are presented in Table 28.

From the obtained results it can be noticed that the bulk dry density was increased only in the M1 mix which contained 20% of calcined clays as a cement replacement. The bulk dry density in the M1 mix was increased by approximately 2% at 28 and 90 days, respectively. This can be attributed to the filling role of the fine calcined clay particles when 20% of the calcined clay replaced the cement hence, a denser matrix has been achieved. The increment in density could also be attributed to that the replacement of the

Table 25
Flexural strength for sand replacement mortar mixes.

Index	C (%)	CC (%)	FA (%)	Fine aggregate (%)		Flexural strength (MPa)	
				Sand	LD	28 day	90 day
ML1	50	35	15	80	20	5.36	5.73
ML2	50	30	20	80	20	4.19	4.82
ML3	50	35	15	70	30	4.75	5.15
ML4	50	30	20	70	30	4.11	4.52

Table 26
Flexural strength for reinforced GM mixes.

Index	Fibers (%)		Flexural strength (MPa)	
	USF	SNF	28 days	90 days
MF0	–	–	5.36	5.73
MF1	0.5	–	5.78	6.59
MF2	–	0.5	6.28	7.05
MF3	0.25	0.25	6.39	7.28
MF4	0.325	0.175	5.82	6.93
MF5	0.175	0.325	7.11	7.68

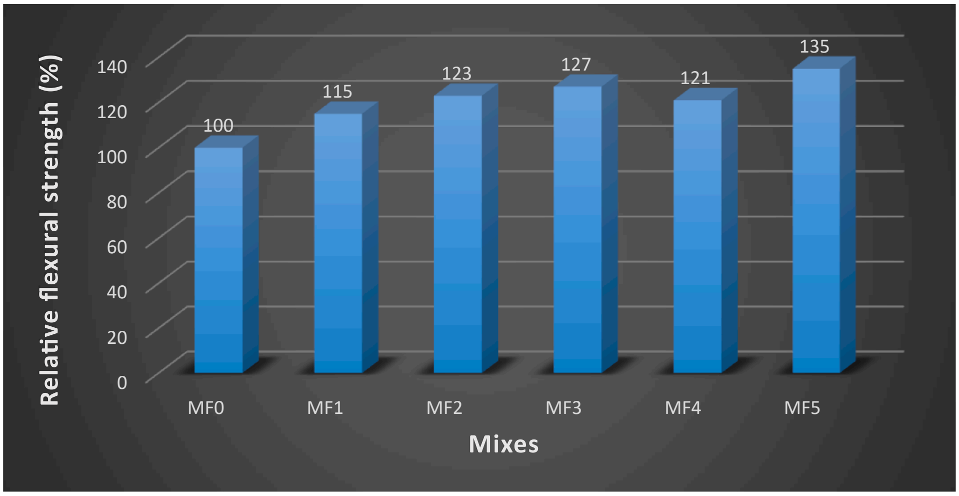

Fig. 15. Relative flexural strength for reinforced GM at 90 days.

Table 27
Dry density for cement replacement GM mixes.

Index	Cement (%)	CC (%)	FA (%)	Dry density (kg/m^3)	
				28 days	90 days
M0	100	0	0	2133.2	2155.3
M1	80	20	0	2183.6	2200.5
M2	75	25	0	2112.9	2133.7
M3	70	30	0	2070.9	2086.3
M4	65	35	0	2050.1	2068.7
M5	60	40	0	2007.5	2029.7
M6	50	40	10	1946.1	1967.8
M7	50	35	15	1877.8	1905.9
M8	50	30	20	1815.4	1828.9

calcined clay was based on mass substitution, therefore the total volume of binding materials (cement + calcined clay) was increased [73].

On the contrary, the bulk dry density for mixes (M2-M8) mixes was uniformly decreased as the amount of cement replacement with supplementary cementitious materials (calcined clay and fly ash) was increased. The density at 90 days was decreased by about 1% in the M2 mix and was gradually decreasing as the amount of cement replacement increased until the decrement was about 15% in the M8 mix, as shown in Fig. 16. This is because the addition of calcined clay and fly ash has significant effects on the composition and the assemblage of the C-(A)-S-H phase. The dissolved silicates and aluminate are increased during the hydration, resulting in increasing the Al/Si ratio and decreasing the Ca/Si ratio, hence the chemical composition of C-(A)-S-H is affected. Moreover, the morphology of the C-(A)-S-H can be changed from fibrillary to foil morphology. This change can affect the density in the hardened mortar [74].

For sand replacement mixes, when LD replaced sand by 20% it can be noticed that the bulk dry density at 90 days was increased by about 5% in the ML1 mix when compared to the M7 mix and was also increased by 5% in the ML2 mix when compared to the M8. The bulk dry density was slightly increased when LD replaced sand by 30%. The density at 90 days was increased by 2% in the ML3 mix when compared to the M7 mix and was also increased in the ML4 mix by 1% when compared to the M8 mix. The reason for this increment is the packing role of LD fines besides the formation of additional hydrate phases due to the reaction between the alumina that exists in the calcined clay and the calcium carbonate from the limestone to form carbo-aluminate phases which can densify the hardened mortar [75].

4.1.2.4. Static modulus of elasticity. The results obtained from the static modulus of elasticity test for the GM reinforced with mono and hybrid fibers are presented in Table 29.

The obtained results revealed that the inclusion of mono and hybrid fibers generally increases the static modulus of elasticity. Because the steel fibers can restrain the internal microstructure [76]. Consequently, the static modulus of elasticity is increased. The results showed that the addition of 0.5% (by volume) of SNF individually increased the modulus of elasticity by about 3.7%, while the addition of USF increased the modulus of elasticity by approximately 2.3%. The difference in the behavior is probably because the two types have different stiffness [77]. However, the hybridization of USF and SNF gave better results. The most significant increment in static modulus of elasticity was witnessed in the M5 mix when a combination of 0.175% USF plus 0.325% SNF (by volume) were included in the mix. The static modulus was increased by about 6.3%. This may be attributed to that a better bonding strength was

Table 28
Dry density for sand replacement GM mixes.

Index	C (%)	CC (%)	FA (%)	Fine aggregate (%)		Dry density (kg/m^3)	
				Sand	LD	28 days	90 days
ML1	50	35	15	80	20	1972.9	1989.6
ML2	50	30	20	80	20	1898.6	1922.5
ML3	50	35	15	70	30	1923.4	1946.2
ML4	50	30	20	70	30	1833.1	1851.2

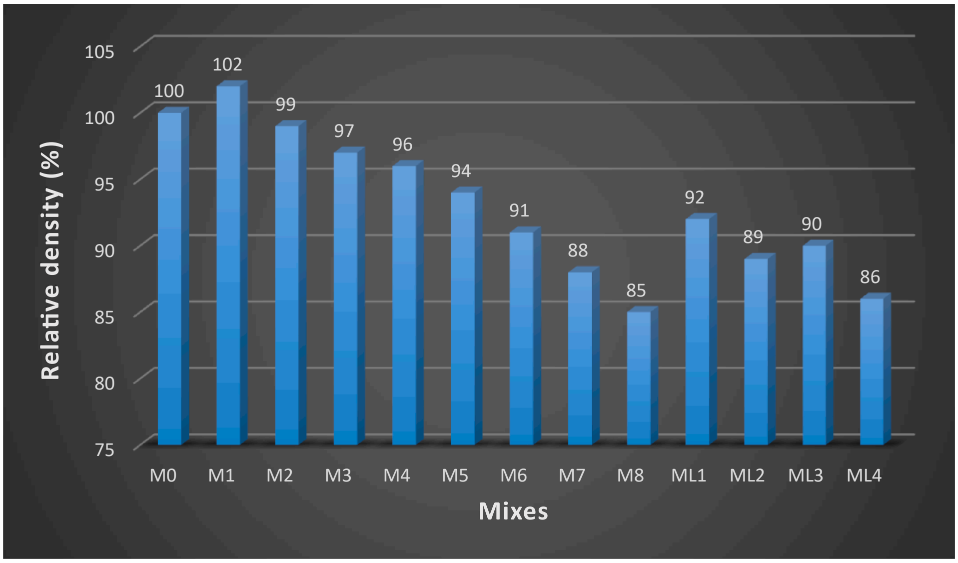

Fig. 16. The relative density for GM mixes at 90 days.

achieved with such hybridization [78].

4.1.2.5. Flexural toughness. The results of the flexural toughness test at 90 days for reinforced GM mixes are presented in Table 30. The results indicate that the inclusion of steel fibers is beneficial in controlling the brittle behavior of the GM by enhancing the post-crack resistance. The load-deflection curve shown in Fig. 17 shows that the control mix did not have any toughness and a sudden failure occurred after reaching the peak load.

From the obtained values of I_5 and I_{10}, it can be observed that there is an obvious improvement in toughness for all mono and hybrid reinforced mixes (MF1-MF5). Because when the cement composite starts cracking, the tensile stresses are transformed from the mortar's matrix to the fibers which can result in deforming or pulling out the fibers. These actions cause additional energy, hence the post-crack behavior is improved [79].

The positive effect of fiber hybridization on the toughness is noticed from the obtained results. The best toughness results were recorded in the mix M5 (0.175% USF + 0.325% SNF). The I_5 and I_{10} values were 3.5 and 4.8, respectively. This can be attributed to the synergic effect of utilizing multi-sized fibers. As the longer fibers (SNF) attend to be pulled out of the matrix during the cracking the smaller fibers (USF) will provide a better frictional bond and the mortar can absorb more energy [80].

4.1.2.6. Drying shrinkage. The drying shrinkage results for reinforced GM mixes at 28, 90 and 120 days, are presented in Table 31.

Table 29
Static modulus of elasticity for reinforced GM mixes.

Index	Fibers (%)		Modulus of elasticity at 90 days (GPa)
	USF	SNF	
MF0	–	–	22.4
MF1	0.5	–	22.9
MF2	–	0.5	23.2
MF3	0.25	0.25	23.4
MF4	0.325	0.175	23.1
MF5	0.175	0.325	23.8

Table 30
Flexural toughness indices for reinforced GM mixes.

Index	Fibers (%)		Indices	
	USF	SNF	I_5	I_{10}
MF0	–	–	–	–
MF1	0.5	–	2.1	3.2
MF2	–	0.5	2.4	3.7
MF3	0.25	0.25	3.0	4.3
MF4	0.325	0.175	2.7	4.0
MF5	0.175	0.325	3.5	4.8

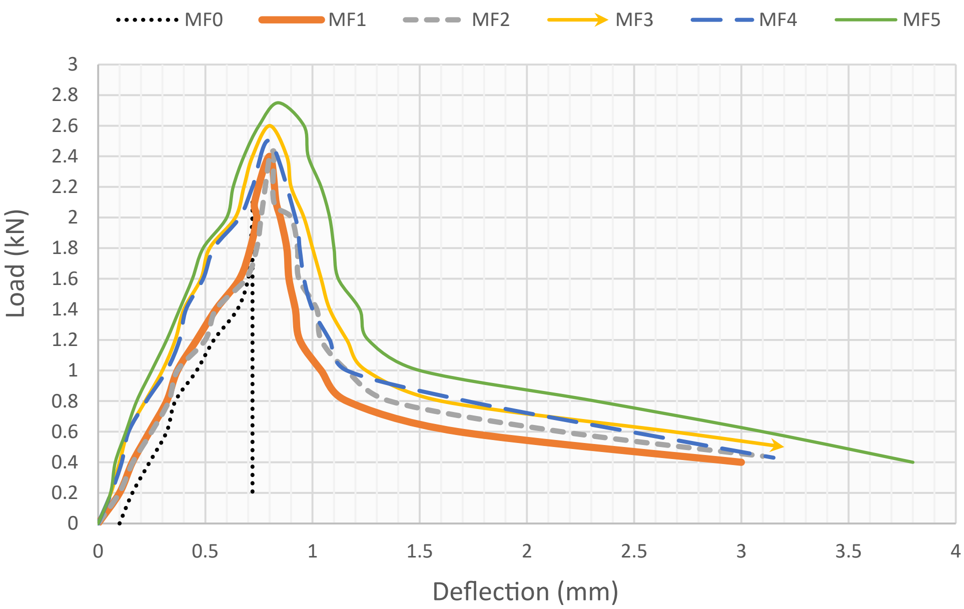

Fig. 17. The load-deflection curve of reinforced GM mixes at 90 days.

The results of the shrinkage test revealed that the addition of 0.5% (by volume) of steel fibers generally reduced the drying shrinkage due to the relatively high stiffness of the steel fibers [81]. The benefit of hybridization was obvious in the mix MF5 (0.175% USF + 0.325% SNF) where the drying shrinkage was reduced by about 45.8%, 51.5% and 52.3% at 28, 90, and 120 days, respectively. The effects of the inclusion of mono and hybrid fibers on the mortar have been extensively discussed in the previous sections. The reductions in the drying shrinkage for the reinforced GM mixes at 120 days are illustrated in Fig. 18.

4.1.3. The effect of GM on reducing the CO_2 emissions

This section aims to assess the carbon dioxide mitigation potentials for the mixes that contain cement and sand substitutions suggested in this study.

In this research, a modern ternary blended cement has been proposed based on the combination of OPC with calcined clay and fly ash. Limestone powder partially substituted the sand for ecological purposes and to improve the properties of the GM.

The two technologies for clay calcination are stationary calcination and flash calcination. The stationary calcination takes place in rotary kilns that are very much similar to traditional clinker kilns. The clay is exposed to heat in the firing chamber for one hour to

Table 31
Drying shrinkage for reinforced GM mixes.

Index	Fibers (%)		Drying shrinkage (%)		
	USF	SNF	28 days	90 days	120 days
MF0	–	–	0.0963	0.1307	0.1506
MF1	0.5	–	0.0845	0.0951	0.1072
MF2	–	0.5	0.0772	0.0848	0.0989
MF3	0.25	0.25	0.0649	0.0746	0.0855
MF4	0.325	0.175	0.0706	0.0798	0.0909
MF5	0.175	0.325	0.0522	0.0634	0.0718

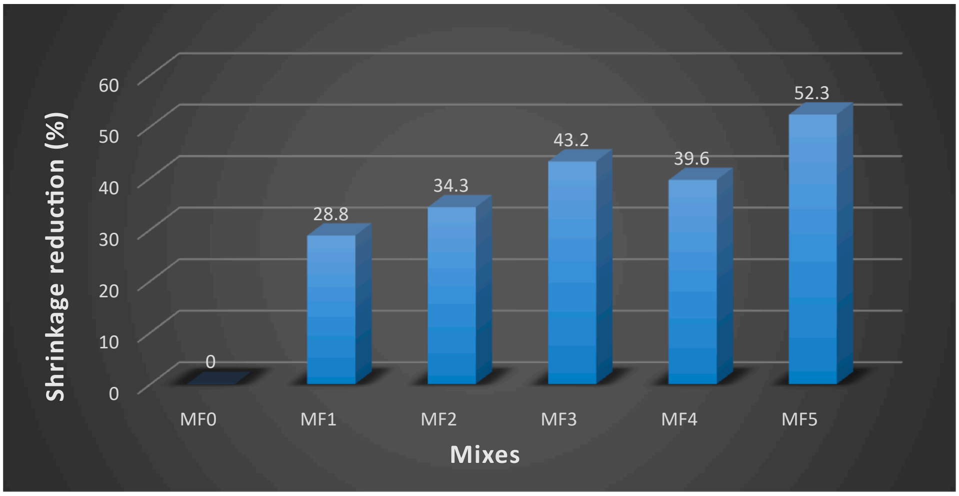

Fig. 18. Drying shrinkage reduction for reinforced GM mixes at 120 days.

achieve the desired properties. Flash calcination takes place in special kilns. The raw clay must be dried and ground before calcination. Then the clay is exposed to a hot gas stream for a few seconds [82]. The CO_2 released from the flash calcination is about 21% lower than the emitted CO_2 from stationary calcination. On the other hand, the cost of stationary calcination is about 50% less than flash calcination. Therefore the calculations in this work are based on stationary calcination. According to previous investigations, the emission factor for the stationary calcination with temperatures around 700–800°C is 0.25 kg CO_2-eq/kg calcined clay. The adopted emission factor for cement was 0.89 kg CO_2-eq/kg cement [83].

Fly ash is a by-product but must be cleansed and procced before utilizing it as an SCM. However, the emission factor estimated by other scientific studies was 0.004 kg CO_2-eq/kg. The limestone powder used in this study is waste material and does not require any treatment before using it as fine aggregate. Therefore the emission factor was considered zero in this assessment process. Based on former works that consider the emissions from quarrying and crushing operations, the adopted emission factor for fine aggregate was 0.0139 kg CO_2-eq/kg. The emission factor for the superplasticizer was 5.2×10^{-6} kg CO_2-eq/kg [84]. The calculations of the estimated CO_2 emissions for GM mixes are shown in Table 32.

The obtained results indicate that CO_2 emissions are related to the percentages of cement and sand replacements and the different emission factors for the GM constituents. For M1-M5 mixes that contained calcined clay as a cement replacement, the estimated reduction in CO_2 emission increased gradually by around 14–28%. Because the emission factor for cement is much higher than calcined clay due to the high amounts of consumed fuel to reach the required temperatures and the released CO_2 from the decomposition of limestone during cement production [85]. For M6-M8 mixes that contained a combination of calcined clay and fly ash as cement replacements, the results showed that the expected CO_2 emissions are decreased by about 37–39% because of the high cement substitutions and the environmental benefit from utilizing by-products such as fly ash instead of cement [86]. Concerning ML1-ML4 mixes that contained limestone powder as a partial sand replacement, the estimated CO_2 emissions are slightly reduced by around 39–41% because limestone powder is waste material and does not require any processing before using it as a fine aggregate [87].

Table 32
Estimations of the released CO_2 from producing GM.

Mix	Cement (kg/m^3)	CC (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	LD (kg/m^3)	SP (kg/m^3)	CO_2 (kg/m^3)
M0	507	0	0	1521	0	1.94	472.4
M1	406	101	0	1521	0	2.48	407.7
M2	380	127	0	1521	0	2.92	391.1
M3	355	152	0	1521	0	3.40	375.1
M4	330	177	0	1521	0	3.89	359.1
M5	304	203	0	1521	0	4.37	342.5
M6	254	203	50	1521	0	4.37	298.2
M7	254	177	76	1521	0	4.37	291.8
M8	254	152	101	1521	0	4.37	285.6
ML1	254	177	76	1217	304	4.37	287.5
ML2	254	152	101	1217	304	4.37	281.4
ML3	254	177	76	1065	456	4.37	285.4
ML4	254	152	101	1065	456	4.37	279.3

5. Conclusions

Based on the obtained results from the testing program of this research, the conclusions can be summarized as follows:

1. The incorporation of 35% CC + 15% FA as cement replacements and 20% LD as a sand replacement affords the highest level of substitution with appropriate fresh and mechanical properties that satisfy the structural requirements of masonry mortar.
2. The clay obtained from the clay deposits located in the north of Mosul city proved to be reactive when thermally treated at the temperature of 750ºC.
3. The incorporation of 30% CC + 20% FA as cement replacements and 30% LD as a sand replacement affords the possibility of reducing the CO_2 emissions by approximately 41%.
4. Utilizing FA as a SCM significantly enhances the workability of fresh mortar that contains considerable amounts of calcined clay, besides the ecological benefit from reducing the overall amount of cement.
5. The use of 20% LD as a sand replacement increases the flowability of the mortar that contains 35% CC + 15% FA by about 55% and the mortar that contains 30% CC + 20% FA by about 31%. Whereas increasing the amount of LD to 30% has a smaller effect in increasing the flowability of both mixes.
6. Replacing the OPC with 25% CC provides the best increment on the compressive strength among other mixes and increases the compressive strength by about 37%, 21%, and 16% at 7,28, and 90 days, respectively. However, while 30% CC as a cement replacement provides similar compressive strength compared to conventional cement.
7. The use of 20% of LD as a sand replacement increases the compressive strength of the mortar that contains 35% CC+ 15% FA by approximately 16%, 13%, and 13% at 7, 28, and 90 days, respectively, and also increases the compressive strength for the mortar that contains 30% CC + 20% FA by approximately 15%, 12%, and 11% at 7, 28, and 90 days, respectively.
8. Reinforcing the GM with 0.5% of SNF as a volumetric fraction rises the compressive strength by about 5%, 6%, and 5% at 7, 28, and 90 days, respectively, while reinforcing the GM with the same amount of USF rises the compressive strength by 1%, 3%, and 2% at the same ages. On the other hand, the hybridization of 0.175% USF + 0.325 SNF improves the compressive strength by 15%, 16%, and 14% at 7, 28, and 90 days.
9. Replacing the OPC with CC by 25% increases the splitting tensile and flexural strength at 90 days by about 18% and 21%, respectively.
10. Reinforcing the GM with 0.5% SNF increases the splitting tensile and flexural strength at 90 days by about 18% and 23%, respectively. While reinforcing the GM with the same amount of USF increases the splitting tensile and flexural strength by about 10% and 15%, respectively.
11. The hybridization of SNF and USF improves the splitting tensile and flexural strength of the GM more than incorporating any of the two types individually. However, the combination of 0175% USF and 0.325% SNF shows the best performance among other hybrid mixes and increases the splitting tensile and flexural strength by about 26% and 34%, respectively.
12. The UPV decreases gradually due to the CC and FA inclusion as partial replacements of cement. Rising the amount of cement replacement up to 50% still gives a rational and acceptable range from UPV.
13. Incorporating USF and SNF individually by 0.5% enhances the static modulus of elasticity by about 2.3% and 3.7%, respectively. However, the hybridization of both types exhibits better performance. Thus, the combination of 0.175% USF and 0.325% SNF increases the static modulus of elasticity by about 6.3%.
14. The toughness indices are enhanced by using steel fibers through improving the post crack behavior of the GM. However, incorporating 0.175% USF + 0.325% SNF exhibits the best performance regarding flexural toughness.
15. The inclusion of steel fibers reduces the drying shrinkage of GM significantly. The hybridization of two types of steel fibers with different dimensions increases the benefit of reducing the drying shrinkage.

6. Recommendations

The recommendations for future studies are stated as follows:

1. Studying the durability of GM through wetting – drying cycles as well as sulfate attack.
2. Investigating the feasibility of producing calcined clay at an industrialscale in Mosul city by employing the typical rotary kilns existing in the local cement factories.
3. Studying the impacts of various types and volume fractions of natural fibers on the characteristics of GM.
4. Evaluating the thermal conductivity and fire resistance of the GM.
5. Investigating the effects of different types of superplasticizers on improving the workability of fresh GM that contains calcined clay.
6. Studying the profit of appending a clay calcination unit to ready mix plants

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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