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Study on Performance, Mechanical Behaviour and Microstructural Characteristics of Eco-Friendly Limestone Calcined Clay Cement (LC3) Concrete with GGBS – A Sustainable Approach

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Abstract

Despite making a significant contribution to global carbon dioxide emissions, the cement industry is rapidly growing all over the world. Utilization of Supplementary Cementitious Materials (SCMs) is the appropriate way to lower these carbon dioxide emissions. A Limestone Calcinated Clay Cement (LC3) is a type developed with calcinated clay, limestone and clinker. The properties of LC3 concrete added with other SCM are very scanty. This study focuses on examining the workability and mechanical properties of LC3 concrete replaced with 10% GGBS for M25, M30 and M50 grade. It was noted that replacing the cement with 10% GGBS decreases compressive strength, modulus of elasticity, split tensile strength and flexural strength by 3.57%-5.84%, 1%-3.7%, 3.92% -15.92% and 7.46% -19.95% respectively. The Ultrasonic Pulse Velocity (UPV) values of the GGBS added LC3 concrete was found to be under the acceptable level. The workability was improved due to the addition of GGBS in LC3 concrete with only a minimum reduction in mechanical properties. Hence, it was concluded that the LC3 cement can be replaced with 10% of GGBS to promote the more sustainable construction practices.

1. Introduction

Globally, around 10 billion cubic meters of concrete was produced every year and this will keep on increasing. Due to this increasing trend and environmental degradation, there is a need to find the alternate source for cement. It was reported that for every ton of cement produced, it was estimated that 0.8 tons of carbon dioxide (CO_2) were released into the atmosphere which was about 5%-8% of total CO_2 emission worldwide [1–4]. There are various techniques to minimize the carbon footprint by utilization of SCMs as a partial replacement for cement in concrete, thereby reducing clinker factor [5, 6]. To produce low carbon cement, industrial by-products such FA, GGBS, and silica fume are frequently used as SCMs. However, majority of these byproducts are not available in large quantities to be used in cement production. Globally, the availability of the conventional SCM like silica fume, GGBS, fly ash, etc., are limited and decreasing in direct proportion to the demand for cement. Also, the large portion of these SCMs are industrial byproducts an existing availability and predicted volume does not meet the expected demand of cement [5, 7, 8]. As such, it is challenging to use these SCMs extensively. On the other hand, calcinated clay will have more benefits in future, since clay minerals are found naturally in earth crust everywhere [9]. While fly ash and other traditional SCMs like GGBS were restricted to specific regions of the world, clay was widely available. Mostly, the kaolinite clay deposits are not pure, which can be considered as impurities like titanium oxides, quartz, calcites [10]. Given their widespread availability and abundance, recent investigations have recognized a potential field of study in the combined use of Lime Stone (LS) and Calcined Clay (CC) [11, 12]. Clay rich in kaolinite is calcined at high temperatures to produce metakaolin, the main reactive component of CC. MK exhibits a rapid pozzolanic reaction that leads to significant improvement in pore and strength characteristics compared to ordinary concrete [13]. On the other hand, the LS has limited reactivity as a pozzolanic material on its own, although its synergistic relationship, when mixed with CC [14]. Ettringite is stabilized as a result of the reactions that produce mono- and hemi-carbon aluminate rather than mono-sulphates [15]. However, the degradation of rheology and workability of the mix is a disadvantage with LS. The layer structure of MK has high specific surface area and retains water between them, therefore raises the superplasticizer need [16, 17]. Utilization of additional SCMs such as GGBS, fly ash, etc., can increases the workability in concrete and helps in mitigating this issue. According to recent research, using intermediate- or low-purity calcinated clay (i.e., kaolinite content) results in good concrete properties [18]. Because intermediate-grade kaolinite clay is more accessible and less costly than the high-grade kaolinite clays needed to produce "pure metakaolin," its use is more feasible. Clays should be calcined to produce the highly reactive amorphous metakaolin phase (AS2) by dehydroxylating crystalline kaolinite before being utilised in cement [14]. The optimal calcination temperature for kaolinitic clay was between 750˚C and 850˚C [19, 20]. Because of the pozzolanic interactions between Portlandite and AS2 (Al2O3.2SiO2), using calcinated clay improves the concrete's pore structure and long-term strength [21]. However, using calcine clay reduces the concrete's early strength growth [5], which is a significant problem for a number of applications. Alite's early strength can be increased by the limestone's ability to quicken its hydration [22]. Moreover, aluminate hydrates can react with the calcium carbonate found in limestone to stabilise ettringite and increase the quantity of hydration products. In fact, if a large amount of limestone is added to SCM with a high alumina content, such as calcined clay, a sizable amount of void-filling carboaluminate phases can develop. These constitute a significant source of SCM due to the widespread availability of lime stone and kaolinite clay [23]. Limestone Calcined Clay Cement (LC3) is a novel binder. Recently, calcined clay and limestone were combined to create Limestone-Calcined Clay Cement (LC3). 40% calcined clay, 20% limestone, and 40% clinker make up its composition [24, 25]. An eco-friendly ternary mixed cement is called LC3. It is composed of three parts: limestone, calcined clay, and clinker. Synergy between the three components is produced by the reaction of the alumina from the calcined clay and the carbonate from the limestone, as well as by the pozzolanic reaction of the calcined clay and the filler effect of the limestone [14]. This makes it possible to replace more clinker and encourages the development of a finer, less linked microstructure, giving the cement superior durability and mechanical qualities.

1.1 Recent Research on LC3 Cement Concrete

Using raw materials from Cuba, Berriel et al. (2016) investigated the properties of LC3 based mortar and concrete [29]. They reported that LC3 mortar and concrete tend to have lower compressive strength at early age, but possess comparable compressive and flexural strength at later ages. It was concluded that the Limestone calcined clay cement can be used in highs-stress applications and can reduce their carbon footprint. Through a life cycle assessment, Junior et al. (2023) assessed the environmental impact of LC3 with kaolinitic residues from the Brazilian Amazon. They developed the 6 various LC3 mixtures with the combinations of gypsum, clinker and metakaolin: limestone in the ratio of 2:1, 1.5:1 and 1.1 replacing 45% and 60% OPC. They reported that utilization of LC3 results in reduction of energy demand by 28% and total CO_2 emission by 38% as compared to conventional cement [30]. The study compared the LC3 cement with traditional Portland cement and commercial blend cement with zeolite in Cuba. It was reported that LC3 cement reduced the production cost by 15%-25% and GHG emission by 20%-23% [31, 32]. Almas et al. (2021) reported that the that the LC3 concrete possess better performance as better early strength gain, low ingress of chloride ion, low water absorption [26]. Gettu et al. (2018) also reported that the LC3 concrete have right resistance to chloride ingress, gas permeation, moisture ingress, sulphate attack [27]. It was reported that the LC3 binder can reduce the CO_2 emission by 30% [28, 29]. The calcined clay is produced by igniting the kaolinite rich clay at 700℃-850℃ instead of high temperature (1450˚C) needed for clinker production [30]. Also, the calcination of the clays does not include the CO2 emission because of the decarbonization of limestone in the cement kiln. Also, the energy consumption of the LC3 cement was less as compared OPC [31]. Thus, its utilization is very advantageous. LC3 was recognized as a valuable low clinker cement with similar strength development properties as OPC [14, 32]. To understand the suitability of the LC3 cement for the large number of applications in the construction industry, it is essential to examine its various properties. Several authors had reported the mechanical and durability properties of the LC3 [13, 23, 27, 33–37]. A model house in Jhansi, SWISS Embassy building in New Delhi to name a few applications of LC3 cement use in India [38]. However, reports on mechanical properties of the LC3 concrete with other SCM like fly ash, GGBS, silica fume, etc. with required workability was not highly found in the earlier studies. Hence, present study is focused on determination of mechanical properties of LC3 concrete partially replaced by cement 10% GGBS to improve the flow properties. Generally, the GGBS incorporated into cement offers improvement in durability and chemical resistance of concrete. LC3 cement, a blend of limestone, calcined clay, and clinker has shown promise for improving the mechanical and durability properties of concrete. By systematically varying the clinker and GGBS content in LC3 formulations, the aim to determine the best mix for superior strength development, durability and microstructural integrity.

2. Materials and Methodology

2.1 Materials

2.1.1 LC3 Cement

The new cement, called LC3, is composed of 40% clinker, 20% limestone, and 40% calcined clay. Clinker, limestone, and calcined clay were the main ingredients used to make LC3 cement. The aluminous and calcareous material was heated to 1400°C in order to process the clinker. Clay that contains more than 40% kaolin material is appropriate for LC3. In addition to traditional rotary kilns, the clay can be calcined in shuttle kilns, flash calcination units, roller hearth kilns, and muffle furnaces. Metakaolin, which contains aluminosilicate and interacts with calcium hydroxide like a traditional pozzolana to form aluminium hydrate and CSH gel, is made from calcined clay that contains kaolin. Tables 1 and 2 displayed the LC3 cement's chemical makeup and physical characteristics.

Table 1 *Physical properties of LC3*

Description	Fineness (m^2/kg)	Normal Consistency (%)	Setting time		Compressive strength (MPa)		
			Initial (mm)	Final (mm)	3 days	7 days	28 days
Results	386	32.5	30	105	34.3	45.3	50.6

Table 2 *Chemical composition of LC3*

Composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Chloride	LOI
%	34.28	30.35	19.45	3.43	1.38	1.58	0.31	0.27	0.027	8.21

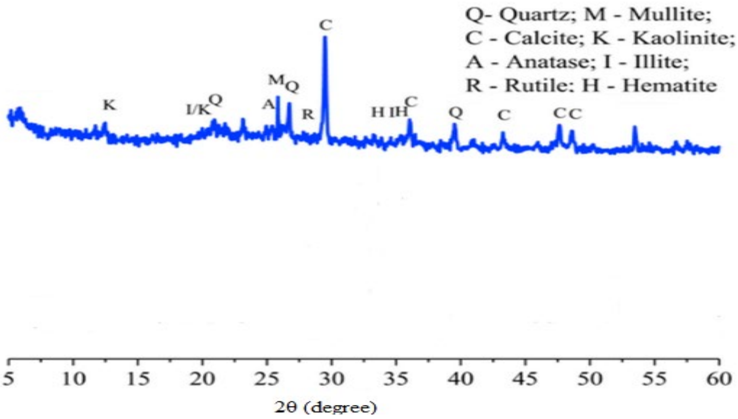

Fig. 1 *XRD of LC3*

2.1.2 GGBS

GGBS is an industrial by-product obtained from the steel industry. The limestone, iron ore and coke are heated in the kiln at temperature of 1500°C – 1600°C [39]. It generally consists of aluminous and grainy siliceous deposits. The GGBS was used as SCM to the LC3 in this study. The chemical composition of GGBS was presented in Table 3.

Table 3 *Chemical composition of GGBS*

Composition	SiO_2	CaO	Al2O3	Fe_2O_3	MgO	Na_2O	K_2O	LOI
%	21.58	55.25	14.88	1.78	2.63	0.015	0.48	1.8

The X-Ray Diffraction (XRD) pattern of the GGBS was acquired using Cu-K (1.5418A°) radiation in the 2-hour range of 10–80 with a step size of 0.02°/1s on a Bruker D2 phase X-ray diffractometer. Figure 2 indicates that GGBS exhibits an amorphous hump at angles of 28°–31° and 10°–20°, confirming the high vitreous calcite concentration in the GGBS sample.

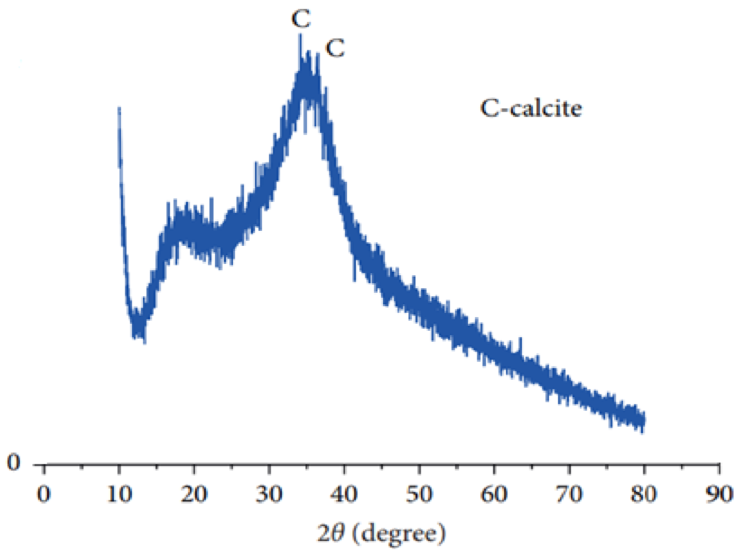

Fig. 2 *XRD of GGBS*

2.1.3 M-Sand

In this study, M-Sand that complied with zone-II as per IS:383-2016 [40] standards were utilized as Fine Aggregate (FA). The specific gravity was 2.6 and fineness modulus was 2.7.

2.1.4 Coarse Aggregates

According to IS: 383-2016 [40], the granite used as coarse aggregate was well-graded, angular, and no larger than 12.5 mm. In addition to having a specific gravity of 2.7 and a fineness modulus of 7.2, the coarse aggregate had a water absorption of 0.62%.

2.1.5 Super Plasticizer

A high range water reducing admixture with specific gravity of 1.82 and solid content of 25% was used as admixture in the concrete.

2.2 Mix Proportioning

The mix portioning for M25, M30 and M50 grade concrete was made as per IS: 10262-2019 guidelines to attain the target strength of the concrete [41]. After various trail mixes with addition of 10% of GGBS into the LC3 concrete mix, an optimized mix was arrived which gives the target strength as presented in table 4. With those optimized mix ratios, the concrete mix were made to test its workability and mechanical properties. Initially, coarse aggregate and M-sand was fed into the mixed and mixed for 2 minutes, Then, the required amount of LC3 and GGS was introduced into the mixture and mixed for 2 minutes in the dry condition. Then, the water and superplasticizer mix were added in the mixer contains LC3 cement, fine and coarse aggregate and mixed for 4 minutes.

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Table 4 *Optimized mix for LC3-M25, LC3-M30 and LC3-M50*

Description	LC3-M30	LC3-M30 + 10% GGBS	LC3-M50	LC3-M50 + 10% GGBS
Cement (kg/m^3)	322	290	340	306
GGBS (kg/m^3)	-	32	-	34
M-Sand (kg/m^3)	783	761	832	832
Coarse Aggregate (kg/m^3)	1209	1204	1120	1120
water/cement ratio	0.55	0.55	0.46	0.46
Super Plasticizer	1.0%	0.8%	1.0%	0.82%

3. Experimental Investigation

The current research aims to analyse the effects of adding 10% GGBS to an LC3 concrete mix. To determine the best performance concrete mix, the mechanical and workability characteristics of the LC3 concrete and the LC3+10% GGBS concrete mix were examined.

3.1 Workability

Workability, which is determined by the slump cone test, is the capacity of freshly mixed concrete to be placed easily. The LC3 concrete and LC3+10% GGBS concrete mixes' slump values were measured during the experiments. In accordance with IS: 1199-1959 norms, the slump cone test was conducted [42]. Four layers of newly mixed concrete were poured into the oil-applied mould, and each layer was tamped 25 times using a 16 mm diameter bar. The filled concrete tends to slide when the mould is lightly removed after it has been filled with concrete. The concrete's height was now measured.

3.2 Compressive Strength Test

The compression test was utilized to measure the compressive strength of the LC3 concrete and LC3+10% GGBS concrete mixes. The 100mm cube test sample was cast and tested after the 28 days of curing using the UTM with a capacity of 2000kN as per the IS: 516-2021 standards with loading rate of 14N/mm^2/ minute [43].

3.3 Modulus of Elasticity

The cylindrical test sample of size 100mm in diameter and 200mm was used to determine the modulus of elasticity of the LC3 concrete and LC3+10% GGBS concrete mixes as per IS-516:2021 guidelines with loading rate of 14N/mm^2/min [43]. The cylindrical test sample was subjected to uniaxial compression in UTM as shown in Figure 3. The deformation occurs during the loading was measured using the dial gauges fixed at certain height of sample. The strain was measured by dividing the gauge reading with length and applied load divided by cross-sectional area of the specimen will give the corresponding stress value. The slope of the corresponding stress-strain curve was used to measure the experimental modulus of elasticity of concrete.

Fig. 3 *Modulus of elasticity test setup*

3.4 Split Tensile Strength Test

The split tensile test was used to measure the tensile strength of LC3 concrete and LC3+10% GGBS concrete mixes. The 200mm height with 100mm diameter cylinder test sample was cast and tested after the 28 days of curing using the UTM with a capacity of 2000kN as per the IS: 5816-1959 standards with loading rate of 1.2N/mm^2/min to 2.4N/mm^2/min [44].

3.5 Flexural Strength Test

The flexural strength of the LC3 concrete and LC3+10% GGBS concrete mixes was determined using the flexural strength of LC3 concrete and LC3+10% GGBS concrete mixes. After the 28 days of curing, the prism test sample of size 100mmx100mmx500mm was tested by placing in the UTM of capacity of 2000 kN under single-point loading system on a simply supported span of 650mm using servo-controlled UTM with a capacity of 2000 kN as per the IS: 5816-1959 standards with loading rate of 1.8kN/min [44].

3.6 Ultrasonic Pulse Velocity (UPV)

The primary objective of this test is to determine how long longitudinal ultrasonic waves take to travel through concrete samples. The ultrasonic pulse velocity method is utilized to examine the material homogeneity and can be useful for identification of defects. For UPV test, concrete specimens for LC3-M25, LC3-M30 and LC3-M50 with addition of 10% of GGBS were made. To prevent any changes in drying shrinkage, the specimens were immediately placed in the water tank for curing, after demold the specimen. Throughout the entire experiment, the length, base and height specimen maintain constant. Every time before the test was conducted, the weight and size were measured.

4. Results and Discussions

4.1 Workability Properties

Figure 4 shows the slump values of the various concrete mixes such as LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete. It was observed that addition of 10% GGBS into the LC3 cement increases the slump value for all grades of concrete. Addition of 10% GGBS to the LC3 cement increases the slump value by 3.33%, 7.14% and 7.69% for M25, M30 and M50 grade of concrete. According to IS: 1199-1959 and IS: 456-2000, the slump values of the developed mixes fall under the category of high and very high degree of workability [42, 45].

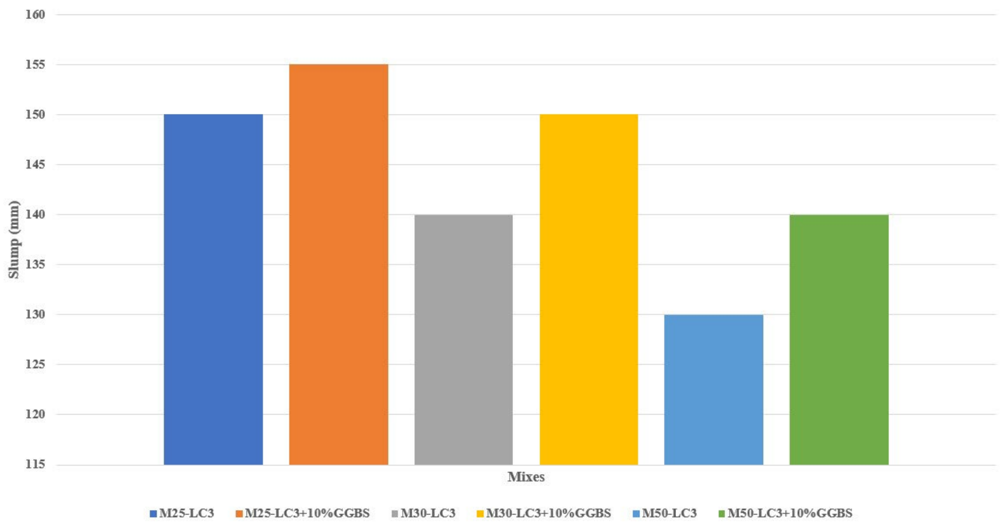


Fig. 4 *Workability of LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete*

When added to cementitious mixtures such as LC3, GGBS, a Supplementary Cementitious Material (SCM), can improve the concrete mix's workability. The finer GGBS particles compared to the cement clinker, which serves as a filler in the mixture, are frequently responsible for this improvement. Because of its spherical particles, GGBS can produce a "ball-bearing" effect in the concrete mixture. More fluidity and better workability are the results of this effect, which lowers friction between particles and makes it easier for them to flow past one another. As cement hydrates, the pozzolanic properties of GGBS react with calcium hydroxide to create more cementitious compounds. A more finer microstructure may result from this reaction, which would increase workability and lower the water requirement. Because GGBS has pozzolanic qualities, it can lower the water need of concrete. By using less water to maintain the appropriate slump value, this decrease in water demand can produce a larger slump without sacrificing the water-to-cement ratio.

4.2 Compressive Strength

Figure 5 displays the compressive strength of the various concrete mixes such as LC3, LC3 + 10% GGBS for M25, M30 and M50 grade concrete. The M25, M30, and M50 grade concrete's compressive strength is reduced when 10% GGBS is added to the LC3 cement. At 7, 14, and 28 days, the compressive strength of M25 grade concrete drops by 3.57%, 4.2%, and 4.52% when 10% GGBS is added to the LC3 cement. At 7, 14, and 28 days, the compressive strength of M30 grade concrete drops by 5.15%, 5.32%, and 5.56% when 10% GGBS is added to the LC3 cement. The compressive strength of M50 grade concrete is reduced by 4.25%, 4.66%, and 5.83% at 7, 14, and 28 days of curing when 10% GGBS is added to the LC3 cement.

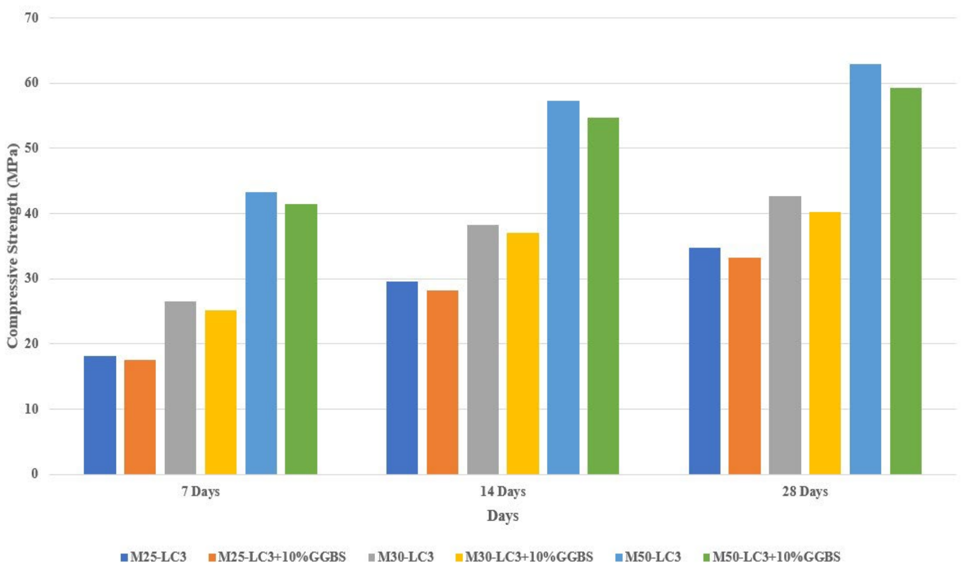


Fig. 5 *Compressive strength of LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete*

The "diluting effect" is one of the main causes of the decrease in compressive strength when GGBS is introduced to LC3. GGBS might not possess the same intrinsic strength as clinker or mixture of calcinated clay and limestone. When GGBS replaces a portion of the clinker, it can dilute the strength-contributing phases, which lowers compressive strength [10]. Also, the incorporation of GGBS can lead to changes in the hydration products formed in LC3 concrete. This may involve the formation of more calcium silicate hydrate (C-S-H) gel, which is a primary contributor to concrete strength. However, the presence of excess C-S-H can lead to a denser microstructure, potentially reducing porosity and impacting compressive strength. Similar findings also observed with addition of GGBS in other cements like OPC, PPC cements, etc. Oner et al. (2007) found 18.33% reductions in the compressive strength with replacement of OPC with 15% GGBS [46]. Lukowski & Salih (2015) reported that the compressive strength OPC concrete replaced with 30%, 50% and 70% of GGBS decreases the compressive strength by 4.6%, 11.3% and 23% [47]. Yamgar & Takkalaki (2018) found 8.12% reductions in the compressive strength with replacement of OPC with GGBS [48]. Chowdary et al. (2017) reported that compressive strength of the PPC concrete replaced with 10% of GGBS decreases the compressive strength by 17.65% at 28 days [49]. The reduction in compressive strength of LC3 concrete in which cement partial replacing with GGBS was found to be less than the OPC, PPC cement partially replaced with GGBS. OPC is well-known for its high early-age strength, characterized by rapid development. However, when OPC is replaced with GGBS, which exhibits a comparatively slower strength development profile, the decrease in early-age compressive strength can be more pronounced. Conversely, PPC already contains a pozzolanic material, typically fly ash, that actively contributes to its long-term strength development. Consequently, when GGBS is incorporated into PPC, the reduction in compressive strength may be less conspicuous when compared to OPC [50]. In the case of LC3 cement, which integrates calcined clay as part of its composition, there exists an inherent capability to enhance early-age strength [51]. However, when LC3 is replaced with GGBS, the reduction rate of compressive strength was less than that of GGBS added with OPC and PPC.

4.3 Elastic Modulus

Figure 6 shows the elastic modulus of the various concrete mixes such as LC3, LC3 + 10% GGBS for M25, M30 and M50 grade concrete. The addition of 10% GGBS into the LC3 cement decreases the elastic modulus of the M25, M30 and M50 grade concrete. The addition of 10% GGBS to the LC3 cement decreases the elastic modulus by 1%, 3.7% and 2.97% at 28 days for M25, M30 and M50 grade concrete respectively. This decrease in elastic modulus suggests that the incorporation of GGBS into the concrete mix makes the material slightly less stiff and less resistant to deformation. It may impact the structural behavior and performance of the concrete in applications where stiffness and load-bearing capacity are critical factors. This decrease is because, when GGBS is used in combination with calcined clay in LC3, there can be interactions between these two Supplementary Cementitious Materials (SCMs). These interactions may affect the overall reactivity of the system and can lead to reductions in properties of concrete [52].

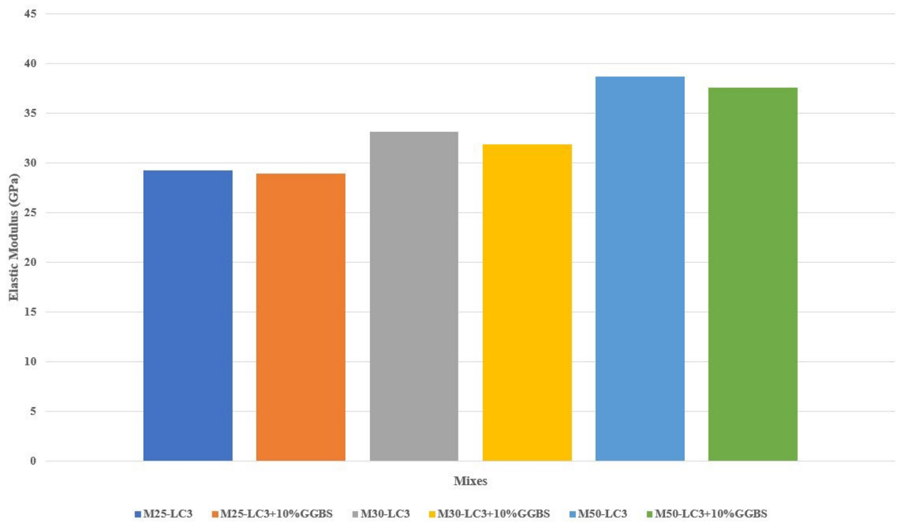


Fig. 6 *Elastic Modulus of LC3, LC3 + 10% GGBS for M25, M30 and M50 grade concrete*

4.4 Split Tensile Strength

Figure 7 displays split tensile strength of the various concrete mixes such as LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete. The M25, M30, and M50 grade concrete's split tensile strength is reduced when 10% GGBS is added to the LC3 cement. The split tensile strength of M25 grade concrete is reduced by 10%, 15.25%, and 10.82% at 7, 14, and 28 days when 10% GGBS is added to the LC3 cement. At 7, 14, and 28 days, the split tensile strength of M30 grade concrete is reduced by 11.27%, 3.92%, and 4.54% when 10% GGBS is added to the LC3 cement. 10% GGBS added to the LC3 cement reduces the split tensile strength of M50 grade concrete by 8.45%, 8.12%, and 7.97% at 7, 14, and 28 days of curing.

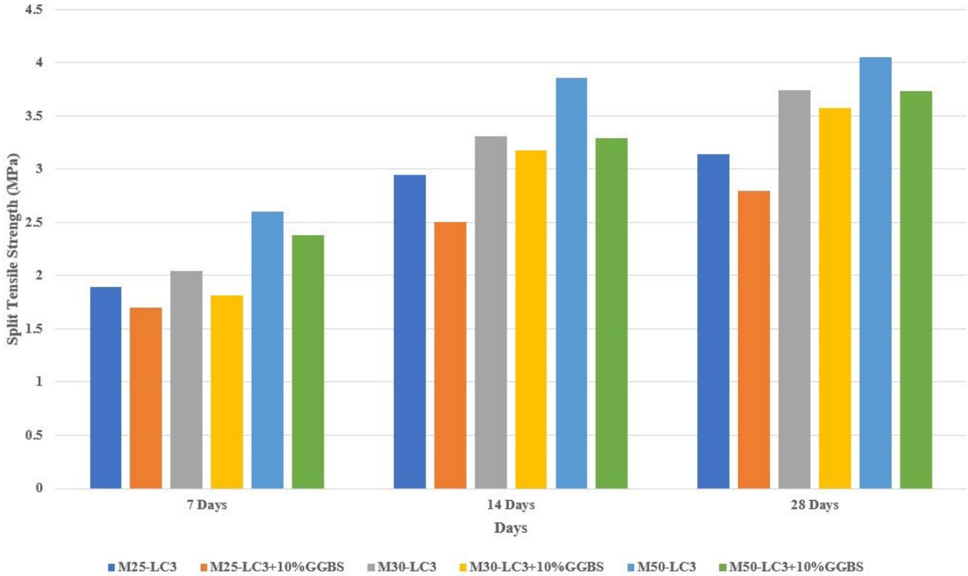


Fig. 7 *Split tensile strength of LC3, LC3 + 10% GGBS for M20, M30 and M50 grade of concrete*

The addition of GGBS can change the hydration products formed in the LC3 concrete. The presence of GGBS can lead to the formation of extra C-S-H gel, thus contributes to concrete strength. However, the presence of excess C-S-H can also lead to denser microstructure and decrease in tensile strength [53]. The reduction in split tensile strength of LC3 cement partial replacing with GGBS was found to be less than the PPC cement partially replaced with GGBS. For examples, Chowdary et al. (2017) reported that replacing 10% of GGBS in the PPC concrete, the split tensile strength reduces by 34.98% at 28 days [49]. Even addition of other SCMs like fly ash, silica fume, metakaolin as binary, ternary or Quaternary mix along with partial replacement of OPC cement with GGBS register high rate of decrease in split tensile strength. Elavarasan et al. (2021) found that replacement of OPC cement with GGBS will reduces the split tensile strength by 35.58% along with addition of metakaolin [54]. Gholampour & Ozbakkaloglu (2017) found that replacement of OPC cement with GGBS will decreases the split tensile strength by 24% along with addition of fly ash [55]. Mohamed et al. (2016) found that replacement of OPC cement with GGBS will decreases the split tensile strength by 10.25% along with combined addition of fly ash and silica fume [56]. The pozzolanic reaction from GGBS is a long-term process that continues to contribute to strength development over time [57]. On the other hand, On the other hand, calcined clay in the LC3 cement contributes on the early-age strength [23]. When these two materials are mixed, they complement each other's strengths. The pozzolanic reaction from GGBS ensures that strength continues to increase over the long term, while the early-age strength from LC3 cement mitigates the potential reduction in strength during the early stages of curing. Compared to concrete mixtures containing GGBS with OPC or PPC, the synergy between GGBS and LC3 cement in the concrete mixture exhibits a more balanced and potentially less pronounced reduction in split tensile strength.

4.5 Flexural Strength

Figure 8 presents the flexural strength of the LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete. The addition of 10% GGBS into the LC3 cement decreases the flexural strength of the M25, M30 and M50 grade concrete. For M25 grade concrete, addition of 10% GGBS to the LC3 cement decreases the flexural strength by 19.95% at 28 days. For M30 grade concrete, addition of 10% GGBS to the LC3 cement decreases flexural strength by 10.42% at 28 days. For M50 grade concrete, addition of 10% GGBS to the LC3 cement decreases flexural strength by 7.46% at 28 days.

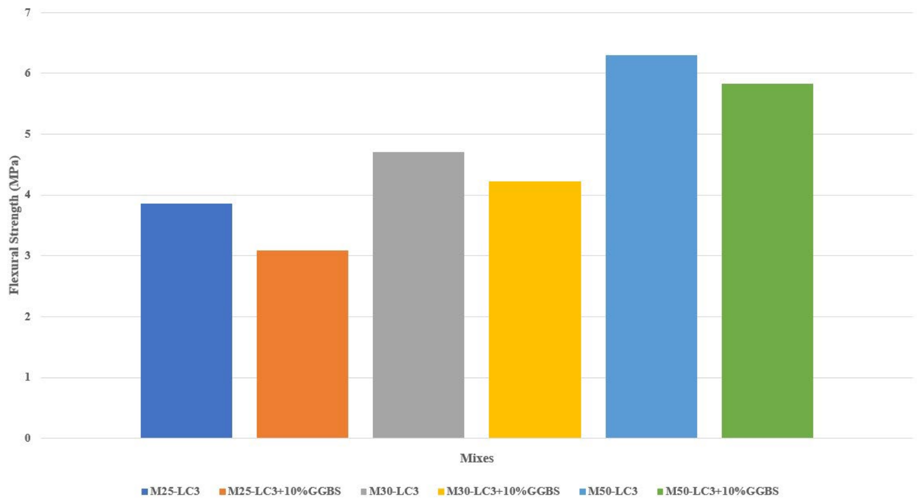


Fig. 8 *Flexural Strength LC3, LC3 + 10% GGBS for M20, M30 and M50 concrete grade*

The addition of GGBS into the LC3 concrete lead to finer pore structures, higher porosity and changes in distribution of hydration products. These alterations in the microstructure can impact the bonding between aggregates and the matrix, thus affects the flexural strength [58]. Variations in microstructural properties can also have an impact on the overall elasticity and deformation behavior of the concrete which are important factor in flexural strength. According to past research, the flexural strength of LC3 cement concrete partially replaced with GGBS decreased at a slower pace than that of OPC and PPC cement. According to Yamgar & Takkalaki (2018), the OPC concrete that was substituted with GGBS had a flexural strength drop rate of 10.46% [48]. According to Tadi & Rao (2022), after 28 days, the flexural strength of the OPC cement concrete that was substituted with GGBS had decreased by 23.5% [59]. Flexural strength decreases rapidly even when more SCMs such as fly ash, silica fume, and metakaolin are added as binary, ternary, or quaternary mixes and OPC cement is partially replaced with GGBS. Gholampour & Ozbakkaloglu (2017) found that replacement of OPC cement with GGBS will decreases the flexural strength by 25% along with addition of fly ash [55]. It was concluded that the reduction rate of flexural strength replacing of GGBS in the LC3 cement concrete was found to be lesser, when compared the flexural strength of OPC concrete [48, 55, 59].

4.6 Ultrasonic Pulse Velocity (UPV)

Figure 9 displays the UPV values of the various concrete mixes such as LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete. The addition of 10% GGBS into the LC3 cement decreases the ultrasonic pulse velocity of the M20, M30 and M50 grade concrete. For M25 grade concrete, addition of 10% GGBS to the LC3 cement decreases the ultrasonic pulse velocity by 1.63%, 1.32% and 3.79% at 7, 14 and 28 days. For M30 grade concrete, addition of 10% GGBS to the LC3 cement decreases ultrasonic pulse velocity by 1.73%, 1.21% and 2.82% at 7, 14 and 28 days. For M50 grade concrete, addition of 10% GGBS to the LC3 cement decreases ultrasonic pulse velocity by 1.77%, 1.88% and 3.03% at 7, 14 and 28 days.

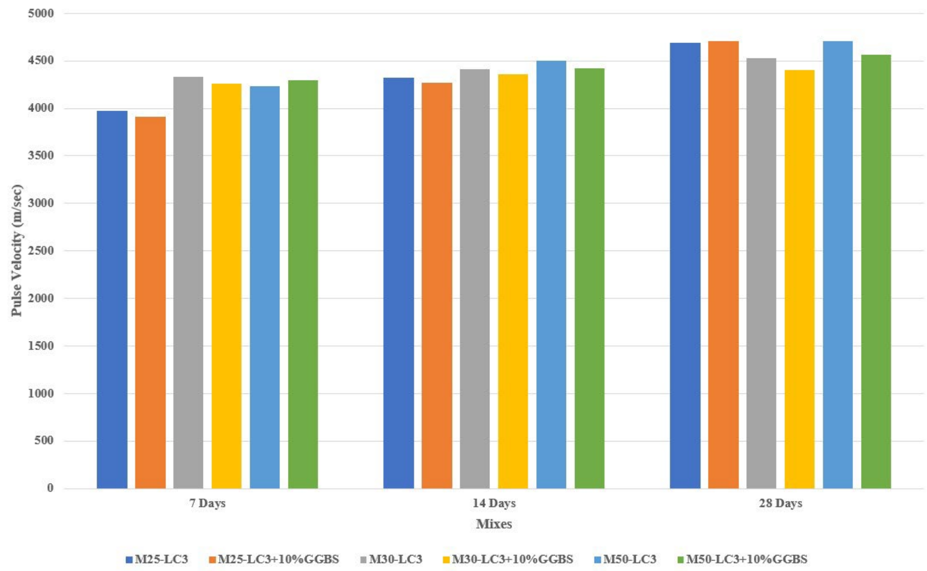
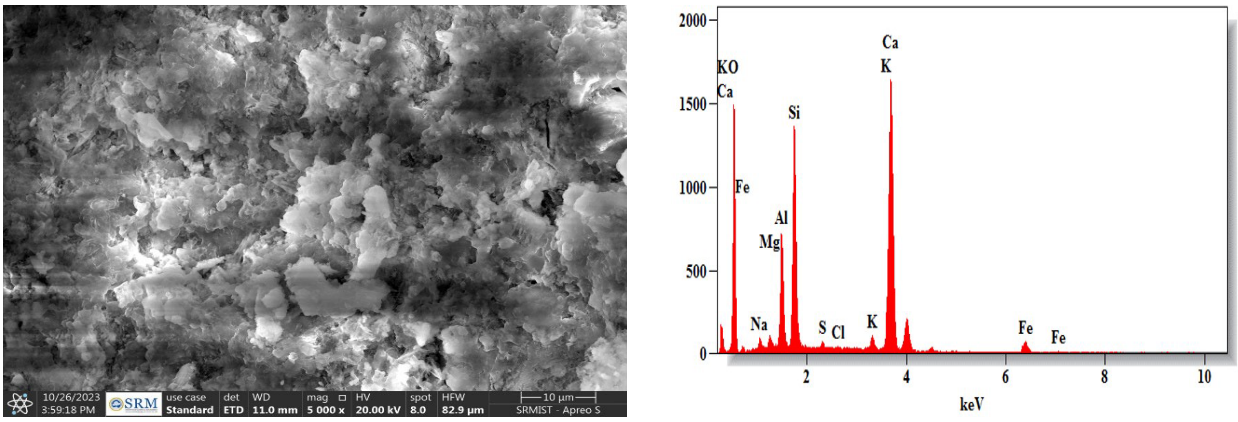


Fig. 9 *Ultrasonic Pulse Velocity LC3, LC3 + 10% GGBS for M25, M30 and M50 grade of concrete*

The sound waves quickly move through a dense, homogenous concrete materials, accordingly, the UPV tends to be higher in well-compacted and high-quality concrete. High UPV values suggest that the concrete is likely free from defects like cracks, voids or delamination. High UPV values are influenced by good concrete mix design, sufficient curing, and adequate compaction. Lower UPV readings values are the sign of defects with the concrete like existence of cracks, voids, honeycombing or insufficient compaction. It was observed that the high-grade concrete possesses high the UPV values than the low-grade concrete. This similar outcome was reported in earlier studies [60–62]. The UPV value of M50-LC3 was higher than M30-LC3; whereas The UPV value of M30-LC3 was higher than M25-LC3. It was observed that replacement of LC2 cement concrete results in slight decrease in UPV values. Addition of 10% GGBS to the M25-LC3 concrete decreases the ultrasonic pulse velocity by 1.63%-3.79% with respective to curing days. Addition of 10% GGBS to the M30-LC3 concrete decreases the ultrasonic pulse velocity by 1.73%-2.82% with respective to curing days. Addition of 10% GGBS to the M50-LC3 concrete decreases the ultrasonic pulse velocity by 1.77%-3.03% with respective to curing days. According to IS 13311-1:1992 [67], high quality concrete is defined as having a UPV value between 3.5 and 4.5 km/s, while excellent quality concrete is defined as having a UPV value greater than 4.5 km/s. Therefore, all of the LC3 concrete mixes that were created, both with and without the 10% GGBS replacement, had UPV values that fell between 3.911 and 4.567 km/s, making them both good and exceptional quality concrete. The GGBS-added LC3 concrete's UPV values ranged from 3.911 to 4.567 km/s. It was clear that adding 10% GGBS to LC3 concrete instead of LC3 cement had no negative impact on the concrete's quality.

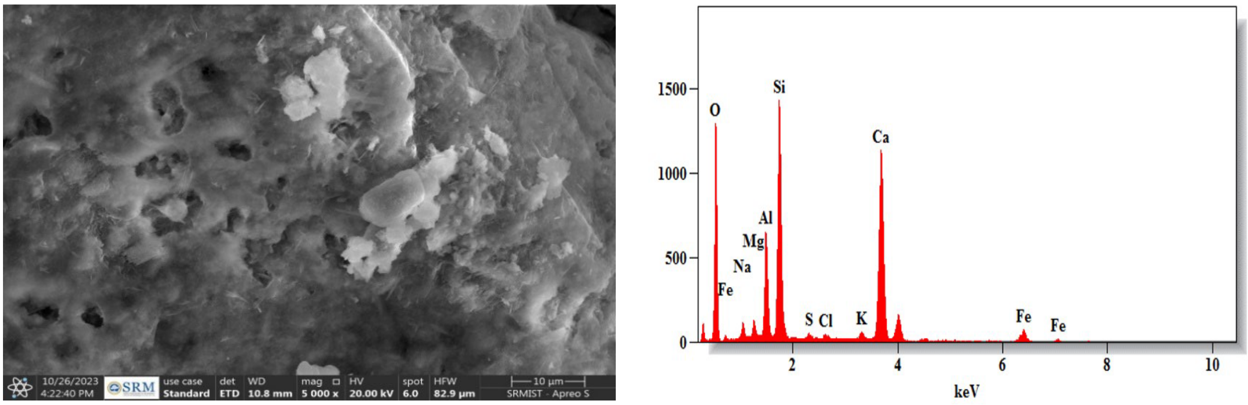
4.7 Microstructural Analysis

Samples of concrete paste SEM micrographs at 10μm magnification was used to examine the various hydration products arrangements like calcium hydroxide, CSH gel and unhydrated cement or GGBS particles in the concrete paste samples. A sample for SEM analysis was taken from the compressive strength tests performed to conduct the micro-structure analysis on concrete samples. When the concrete samples are viewed at higher magnifications, the hydration products and particles of unhydrated cement are visible. The SEM makes it possible to define the microstructure of the concrete and cement [63, 64]. The EDX spectrum was commonly used to evaluate the quality of the concrete. For example, the ratio of calcium to silica (Ca/Si) is a crucial indicator of the strength of the concrete. A strong concrete is indicated by a high Ca/Si ratio, and a weak concrete is indicated by a low Ca/Si ratio. The EDX pattern of the hydration products and SEM images were analysed for LC3 concrete and LC3 with GGBS added concrete and their results are presented from Figure 10-15.



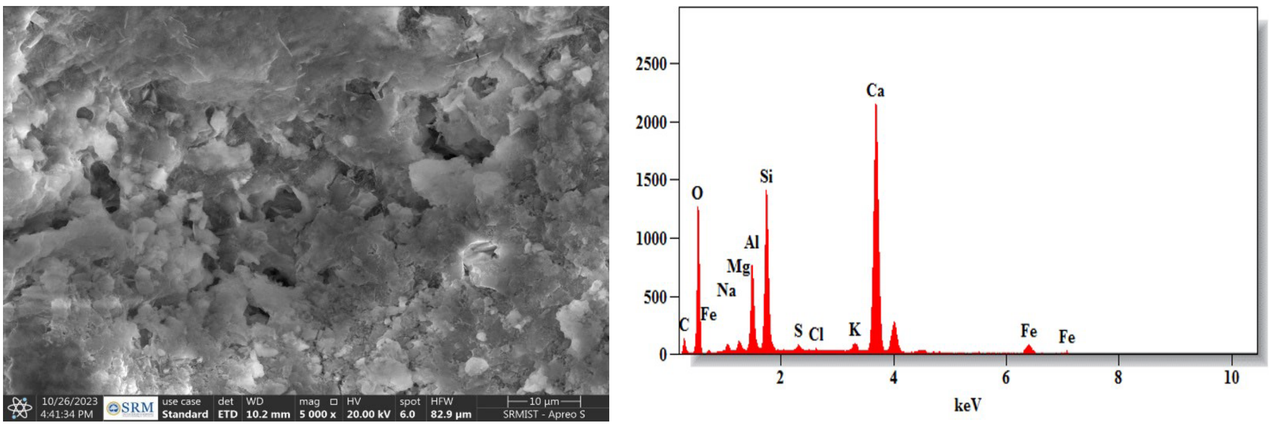
(a) (b)

Fig. 10 *(a) SEM and (b) EDX image of M25-LC3*



(a) (b)

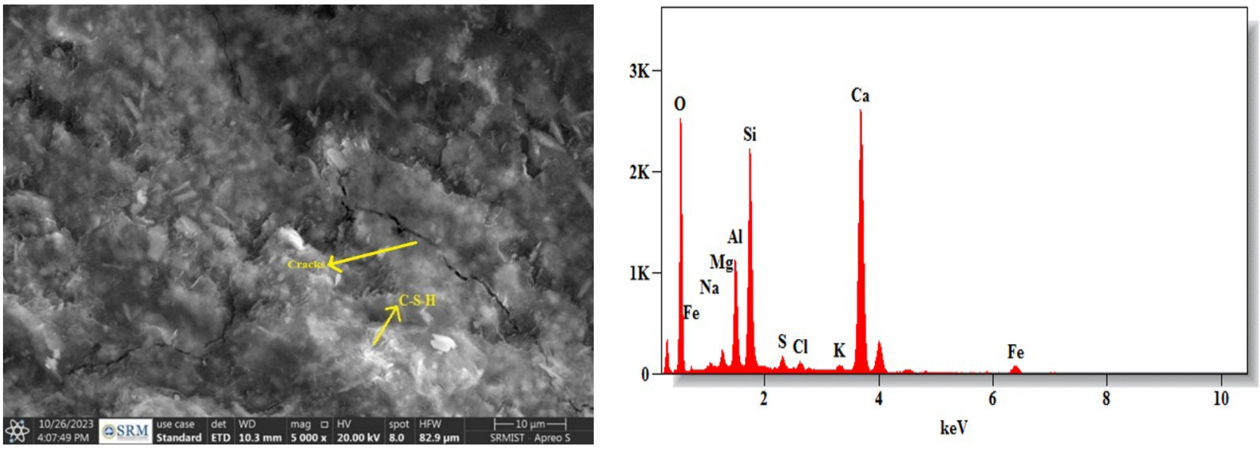
Fig. 11 *(a)SEM and (b)EDX image of M30-LC3*



(a) (b)

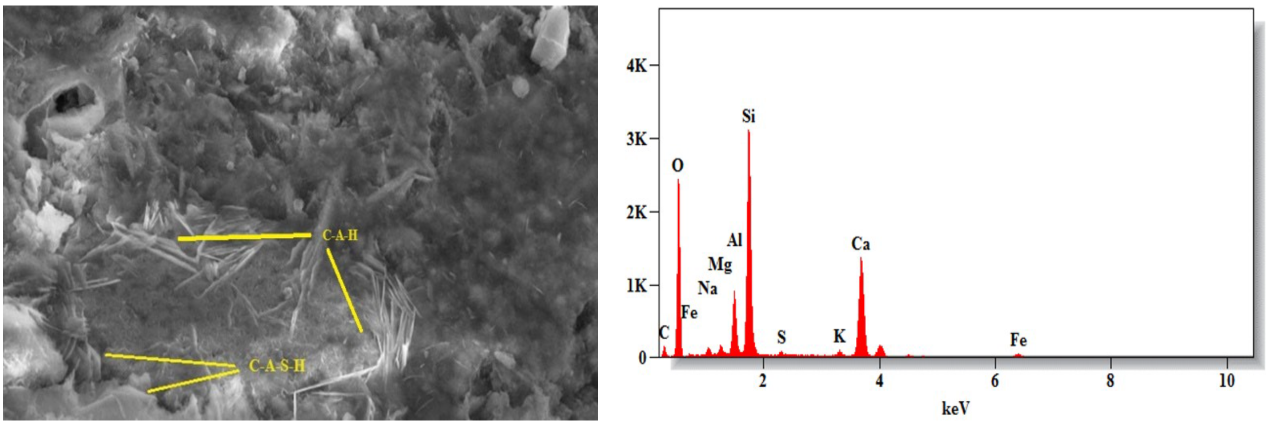
Fig. 12 *(a) SEM and (b) EDX image of M50-LC3*

Figure 10–12 shows the microscopic and EDX image of the M25–LC3, M30–LC3 and M50–LC3 concrete samples. Variations in the element composition from various points of examination were visible in the SEM image. Several elements, including Ca, SI, K, Fe, Mg, Fe, Na, S, and Cl, are present in the concrete samples M25–LC3, M30–LC3, and M50–LC3, according to their EDX spectra. The relative abundance of each element is shown by the strength of the peaks in the spectrum. The presence of C-S-H phases and carbo-aluminates is indicated by the prominent components Si, O, C, and Ca. This improves overall strength, decreases porosity, and aids in space filling. The increased compressive strength has been confirmed by other descriptions of the beneficial effects of carbo-aluminates precipitation on the mechanical properties [14, 65].



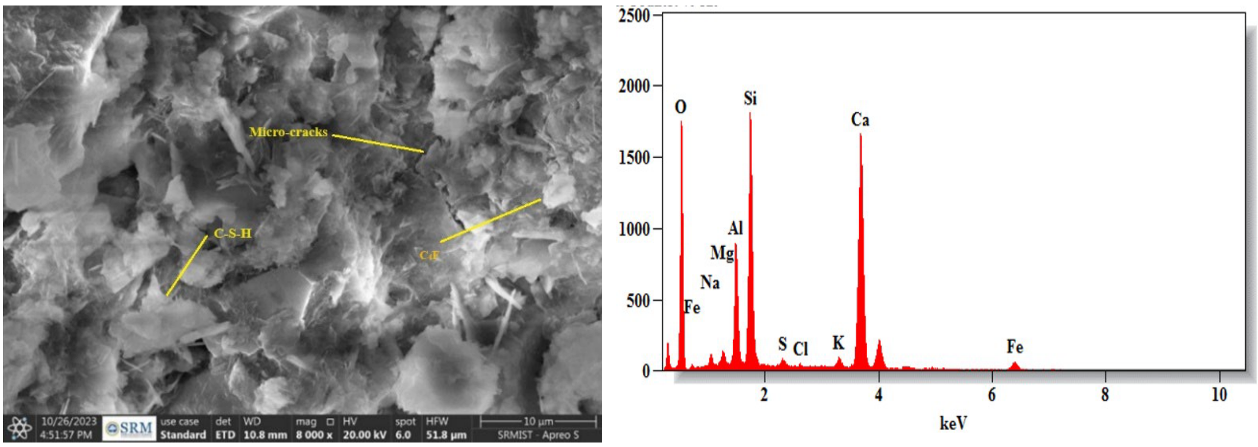
(a) **(b)**

Fig. 13 *SEM and EDX image of M25-LC3+10% GGBS*



(a) **(b)**

Fig. 14 *SEM and EDX image of M30-LC3+10% GGBS*



(a) **(b)**

Fig. 15 *SEM and EDX image of M50-LC3+10% GGBS*

Figure 13 shows the microscopic and EDX image of the M25-LC3+10% GGBS concrete samples. EDX image of M25-LC3+10% GGBS sample reveals that elemental composition which composed of elements such as Ca, Si, Al, Mg, Na, K, Fe, S and Cl are represented as peaks in the spectrum. The presence of Ca, Si and O are the most abundant elements in the concrete. The presence of high percentage of these elements suggests the presence of calcium silicate hydrate (C-S-H) phases. Also, addition of GGBS react with calcium hydroxide which is produced during the hydration of cement to form a calcium silicate hydrate gel. This gel will bind the particles together and strengthen the concrete. From the SEM mages, it was observed that there was cracks as found in the M25-LC3+10% GGBS concrete, however, these cracks are not observed in M25-LC3 concrete samples. The addition of GGBS can lead to increased shrinkage, which might result in cracking [66]. This induces the reduction in compressive strength. Figure 14 shows the microscopic and EDX image of the M30-LC3+10% GGBS concrete samples. EDX image of M30-LC3+10% GGBS sample reveals that elemental composition which composed of elements such as Ca, Si, Al, Mg, Na, K, Fe, S, C, O and Cl are represented as peaks in the spectrum. The presence of Ca, Si and O are the most abundant elements in the concrete. The presence of high percentage of the prominent components such as O, Si, C, and Ca indicate the existence of C-S-H phases and carbo-aluminates. There were several hexagonal pillars as observed that are mainly elements of Ca, S, Al and O. The C-A-H of those elements react with a high percentage of sulfur to form C-A-S-H or ettringite. Figure 15 shows the microscopic and EDX image of the M50-LC3+10% GGBS concrete samples. The EDX spectrum shows that the concrete is mainly composed of calcium (Ca), silicon (Si), aluminum (Al), magnesium (Mg), iron (Fe), sodium (Na), sulfur (S), chlorine (Cl) and potassium (K). The most intense peaks in the spectrum are due to calcium, which is the main component of cement. The peaks at lower energies are due to the other elements in the concrete. There was a significant drop in the amount of calcium hydroxide. Additionally, it is evident that the addition of GGBS fills the voids in the microstructure. Some GGBS particles may remain unhydrated due to their slower reactivity. These particles appear as angular, glassy inclusions in the SEM image. Their presence may have an impact on the long-term strength gain and shrinkage behavior of the concrete. SEM can also reveal the presence of microcracks and pores in the concrete. GGBS can help refine the pore structure, leading to denser and less permeable concrete. A large decrease in the amount of calcium hydroxide can be detected. C2S and C3S achieved their highest values, while CH reached its lowest. The predominate elements include Si, C, Fe, O and Ca. It is believed that C-S-H, tetra-calcium ferrite (C4F) and carbo-aluminates are formed.

5. Conclusions

The feasibility of using GGBS as a SCM for the LC3 cement concrete by testing its workability properties, mechanical properties and non-destructive testing is examined. The various conclusion as derived from the experimental investigations are as follows;

- ✓ A few case studies towards the use of LC3 in India provides ample use of LC3 applications in the civil construction industry. This study suggest that LC3 could play a significant role in reducing the construction industry's carbon footprint around the world and possess properties comparable to the OPC.
- ✓ The partial replacement of LC3 cement with 10% of GGBS demonstrates an improvement in workability. The inclusion of GGBS improves the ease with which the concrete may be mixed, placed and compacted, making it more workable for construction applications.
- ✓ The partial replacement of LC3 cement with 10% of GGBS decrease the compressive strength by 3.57%-5.84% with respective of grade of concrete and curing days. The finding indicates that LC3 is replaced with GGBS, the reduction rate of compressive strength was less than the GGBS added into OPC and PPC.
- ✓ The partial replacement of LC3 cement with 10% of GGBS decrease the split tensile strength was 3.92% -15.92%. with respective of grade of concrete and curing days. These results indicate that split tensile strength of the concrete is differently and grade-dependently by the addition of GGBS to LC3 cement, with M20 grade showing the highest initial reduction; while M30 and M50 grades exhibits more steady declines over time.
- ✓ There was a slight decline in flexural strength of the LC3 cement concrete with partial replacement of cement with 10% of GGBS. The decline rate of flexural strength of the GGBS added LC3 cement concrete was 7.46% -19.95% for M25-LC3, M30-LC3 and M50-LC3 at 28 days.
- ✓ Addition of 10% GGBS to the LC3 concrete decreases the ultrasonic pulse velocity by 1.63%-3.03% with respective to grade of concrete and curing days. However, the partial replacement of LC3 cement with 10% of GGBS does not show any adverse effect on the quality of concrete.
- ✓ The micro-structural analysis of the LC3 concrete and LC3-GGBS added concrete reveals that there was cracks as observed in the LC3-GGBS added concrete, which might be induce the reduction in strength on addition of GGBS.

It was found that the partial replacement of LC3 cement with 10% of GGBS shows insignificant effect on workability and mechanical properties of the LC3 cement. However, LC3 cement partially replaced with 10% of GGBS can promote more sustainable construction practices. This study strongly recommended to use the GGBS as partial replacement for cement for production of the LC3 concrete, which results in reduced in CO_2 emission, having more economical and sustainable concrete. In future, this work can be extended with addition of reinforcement materials like fibers to compensate the slight decline in the mechanical properties of GGBS added LC3 cement concrete.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

K Venkataraman: ***Methodology, Formal Analysis, Investigation, Resourses, Writing – Original Draft, Visualization***; *P R Kannan Rajkumar:* ***Conceptualization, Data Curation, Writing – Review & Editing, Supervision***.

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