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RESEARCH

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Incorporating Limestone Powder and Ground Granulated Blast Furnace Slag in Ultra-high Performance Concrete to Enhance Sustainability

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Abstract

While ultra-high performance concrete (UHPC) offers numerous advantages, it also presents specific challenges, primarily due to its high cost and excessive cement content, which can pose sustainability concerns. To address this challenge, this study aims to develop cost-effective and sustainable UHPC mixtures by incorporating ground granulated blast furnace slag (GGBFS) and limestone powder (LP) as partial replacements for portland cement. Eight fiber-reinforced UHPC mixtures were investigated, with a water-to-cementitious materials (w/cm) ratio of 0.15. In four of the UHPC mixtures, 25% of the cement was replaced with GGBFS, and further, LP was added as a mineral filler, partially substituting up to 20% of the cement. In the remaining four mixtures, cement was replaced with only LP up to 20% (without GGBFS). The 28-day compressive strength of the UHPC mixture with 25% GGBFS and 20% LP was 149 MPa, 3.50% lower than the mixture without GGBFS. Its 28-day flexural strength decreased by 30%. Increasing LP replacement reduced drying and autogenous shrinkage, with a 29% shrinkage reduction at 20% LP replacement. Moreover, UHPC mixtures with GGBFS exhibited lower shrinkage compared to those without GGBFS for all LP replacements up to 20%. For evaluating the sustainability of UHPC mixtures, the cement composition index (CCI) and clinker to cement ratio (CCR) were determined. For 20% LP replacement with 25% GGBFS, CCI was 3.6 and the CCR was 0.5, 38% decrease from the global clinker to cement ratio. Overall, 20% LP replacement UHPC mixtures with and without GGBFS can produce UHPC class performance and reduce the environmental impact.

Keywords Eco-friendly UHPC, Supplementary cementitious materials, Mechanical properties, Durability, Sustainability

1 Introduction

In the field of concrete technology, ongoing advancements have been a hallmark for decades. Recently, Ultra-High Performance Concrete (UHPC) has emerged as a promising construction material because of its excellent mechanical and durability properties. UHPC is an advanced fiber reinforced composite material characterized by compressive strengths exceeding 120 MPa and sustained post-cracking tensile strength greater than 15 MPa (Akhnoukh & Buckhalter, 2021). UHPC combines the characteristics of three specialized concrete types: self-consolidating concrete's flow and passing abilities, high-performance concrete's strength, and fiber-reinforced concrete's ductility and post-cracking strength (Zaid et al., 2023). The superior durability properties of UHPC can extend the service life of structures to more than 200 years, which is two- to three-fold greater

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than the service life of the structures made with normal strength concrete (Horák et al., 2022; Sohail et al., 2021). Additionally, the high mechanical strength of UHPC can facilitate significant reductions in the size of concrete elements. Field cast UHPC is used in connections between prefabricated bridge elements, pile cap closure pores, bridge deck overlays and repairs, and as a grout for bridge shear keys. In addition to bridge applications, building components such as cladding and roof components have been UHPC applications in the last decade. UHPC has also been used widely to repair and protect hydraulic structures and high-speed railways.

UHPC mixtures are typically produced with a very high cementitious materials content, around 40% to 50% per cubic yard of UHPC and a low water-to-cementitious materials ratio (w/cm) using only cement and silica fume (SF) as the cementitious components (Akhnoukh & Buckhalter, 2021). The common guideline to produce UHPC include removal of coarse aggregate and use of fine sand (particle size < 600 μm) to enhance mixture homogeneity, addition of steel fibers to improve ductility, application of pre-setting pressure and post-setting heat treatment to improve mechanical properties and microstructure, addition of SF to improve density and produce secondary calcium silicate hydrates, and inclusion of high range water reducing admixtures (HRWRAs) to facilitate a low w/cm ratio with enough workability for placement and consolidation (Richard & Cheyrezy, 1995).

Materials being used in UHPC are often shipped long distances, internationally in most cases, increasing the overall cost. Additionally, strict requirements on the chemistry of the cement and SF increase the cost of commercially available, prepackaged UHPC products. Furthermore, the cement content used in UHPC mixtures is approximately three times that of conventional concrete (800–1000 kg/m^3) (Jiao et al., 2020; Shi et al., 2019; Yang et al., 2020a), which creates sustainability challenges as cement production is an energy intensive process that contributes to CO_2 emissions. Therefore, despite its remarkable performance, UHPC is viewed as a concrete product with substantial energy consumption, which runs counter to the prevailing trends in sustainable development. Consequently, there is a strong impetus to create a more environmentally friendly UHPC that is cost-effective and has a reduced carbon footprint, aiming to enhance its acceptance and broaden its application in structural engineering (Ding et al., 2021a; Shi et al., 2019; Wang et al. 2018). Complete hydration of cement with low w/cm ratio and high cementitious material is a challenge. Similarly, Yu et al. (2014) reported that the hydration degree after 28 days ranged between 52 and 68%. Korpa et al. (2009) reported that only 30–35% of cement will be hydrated for the ultra-low w/cm ratios of UHPC mixtures, meaning the remaining cement would be unhydrated and acts as expensive filler in the binder system. Consequently, there is interest to replace part of the cement with SCMs such as SF, fly ash (FA), ground granulated blast furnace slag (GGBFS) and mineral fillers such as limestone powder (LP) (Hassan et al., 2012; Tuan et al., 2011). Furthermore, suitable utilization of SCMs can not only efficiently reduce cost and environmental pressures but also confer advantages to several characteristics of UHPC. These benefits encompass long-term strength, dimensional stability, enhanced pore structure, and resistance to corrosion (Pyo & Kim, 2017; Tuan et al., 2011). As an example, Burroughs et al. (Burroughs et al., 2017) and Yu et al. (2015) employed LP to substitute cement at various proportions in their research. It was reported that this substitution enhanced the flowability and increased the compressive strength of the UHPC matrix by optimizing its microstructure. In a separate study, it was reported that lead–zinc tailings as SCMs effectively reduced autogenous shrinkage without compromising the UHPC's compressive strength (Wang et al., 2018). Meanwhile, Dixit et al. (2019) explored the impact of replacing cement with biochar on internal curing effects. Their findings indicated that biochar improved hydration, resulting in a denser microstructure in the UHPC matrix. Nevertheless, there are challenges arising from the growing demand for industrial byproducts in recent years. For example, SF, the primary SCM in UHPC, is often substituted with inexpensive class F fly ash due to its higher cost compared to cement and other SCMs in North America. However, the future availability of FA is uncertain as the energy industry moves toward renewable energy. Amidst these challenges, researchers are exploring alternative SCMs that can not only mitigate cost concerns but also contribute to the development of sustainable UHPC with a reduced carbon footprint. Two promising candidates in this regard are GGBFS and LP.

GGBFS is a highly cementitious byproduct of iron extraction in a blast furnace, and is a suitable alternative for cement, FA, and SF in UHPC. It is abundant in silica and alumina phases (Xu et al., 2017). Its inclusion to partially replace cement has been explored due to its hydraulic behavior, as it reacts with water and produces calcium silicate hydrate (C–S–H) gel, contributing to the strength and durability of concrete (Gupta, 2016). GGBFS used to replace cement up to 60 wt.% led to an increase in compressive strength of up to 10% after 28 days of curing (Gupta, 2016; Yu et al., 2015). When FA, GGBFS, and LP were used as partial replacements for cement, up to 30% by mass, the UHPC mixtures containing GGBFS exhibited superior mechanical properties compared to those containing FA or LP (Yu et al., 2015). Hydration rate in UHPC mixtures containing GGBFS is typically greater than those containing FA. This is due to the fact that the pozzolanic reaction of FA can be inhibited in the specific cementitious system of UHPC, which typically features a very low water-to-cement ratio and a high dosage of HRWRA (Yu et al., 2015). As a result, only a limited amount of FA can react with the available calcium hydroxide.

Another potential candidate for the partial replacement for cement is LP. Since UHPC is developed with low w/cm ratio (<0.20) and high cementitious materials content, complete hydration of cement is not possible (Korpa et al., 2009; Yu et al., 2015), which suggests that the remaining cement would remain unhydrated and acts as expensive filler in the system. Consequently, there is interest in replacing a portion of the cement with SCMs. LP replacement ratio can be high in UHPC since more than half of the cement in UHPC is simply used as a physical filler (Huang et al., 2017, Kang et al., 2019; Yu et al., 2014). Efforts to use GGBFS, FA, and rice husk ash as alternatives to SCMs are limited due to availability. LP as a partial replacement to cement can significantly contribute to the economic and environmental production of cement-based materials, due to advantages such as stable supply, ease of quality control, worldwide availability, and reasonable price. LP was used to replace cement and SF in UHPC (Burroughs et al., 2017), and although the workability and mixing time were improved, the compressive strength of UHPC decreased with increasing LP content (Kang et al., 2019). The degree of secondary pozzolanic hydration of LP with SF is more intensive than C_3S or C_2S hydration that enhances the later age strength development potential (Li et al., 2020a), with the optimum LP dosage being around 50%. Replacing cement with LP ($<74\%$) promoted cement hydration (Huang et al., 2017), which is encouraging because the hydration degree of typical UHPC with a low w/cm ratio can be as low as 35%, and the unhydrated cement remains as expensive filler, which is uneconomical. However, increasing LP content also increases porosity and decreases compressive strength (Li et al., 2020a).

The present study aims to develop sustainable and cost effective UHPC mixtures by replacing a portion of cement with GGBFS and LP. This study was conducted to understand the effects of LP as a partial replacement for cement in UHPC mixtures by replacing either 0% or 25% by weight of cement with GGBFS while LP dosage was varied from 0 to 20% by weight of cement. Workability, mechanical properties, and drying and autogenous shrinkage were evaluated.

2 Materials, Mixture Proportioning, and Experimental Methods

2.1 Materials

Type I/II ordinary portland cement (OPC) and commercially available SF, GGBFS, and LP were used for this research. Physical and chemical properties of these materials are presented in Table 1. Locally available sand with maximum particle size of 4.75 mm (ASTM #4) was used. The particle size range of LP used in this study was 44 to 841 microns. 13 mm long straight steel fibers with an aspect ratio of 65 were added to the mixtures to improve ductility. Commercially available polycarboxylate-based HRWRA was used to achieve desired workability.

Figure 1 shows the particle size distribution of OPC, SF, FA, GGBFS and LP. The GGBFS has a particle size distribution ranging from approximately 0.01–56 μm, similar to OPC (0.05–71 μm). Similarly, Fig. 1 indicates that LP has a particle size distribution range from 0.01 to 36 μm. This particle size distribution allows GGBFS and LP to integrate seamlessly within the existing particle framework of UHPC mixture with OPC. The use of fine fillers like LP and SCMs such as GGBFS, FA and SF can improve the packing density, leading to improved mechanical properties and durability of the concrete mix (Ullah et al., 2022).

Table 1 Chemical composition and physical properties of cementitious materials used

Chemical compounds (%)	Cement	Silica fume	Fly ash	GGBFS	LP
SiO_2	20.2	96.9	38.03	30–40	1
Al_2O_3	4.3	0.2	18.44	7–18	0.15
Fe_2O_3	2.8	0.2	5.16	0.1–1.8	0.15
CaO	63.8	0.3	16.05	30–50	–
MgO	1.6	0.2	3.73	2–14	–
SO_3	0.35	0.1	3.3	2.5	–
Na_2O	–	0.2	9.2	–	–
K_2O	–	0.3	0.96	–	–
MgCO3	–	–	–	–	44.3
$CaCO_3$	–	–	–	–	54.2
$Ca(SO_4).2H_2O$				≤ 2	
Mn				≤ 1	
S	–	–	–	1	–
Loss on ignition	0.88	2.17	2.1	≤ 2	–
Insoluble residue	0.34	–	–	–	–
Relative density	3.15	2.24	2.58	2.91	1.28
Moisture content (%)	–	0.04	0.2	–	0.2
Blane fineness (m^2/kg)	401	–	–	542	–

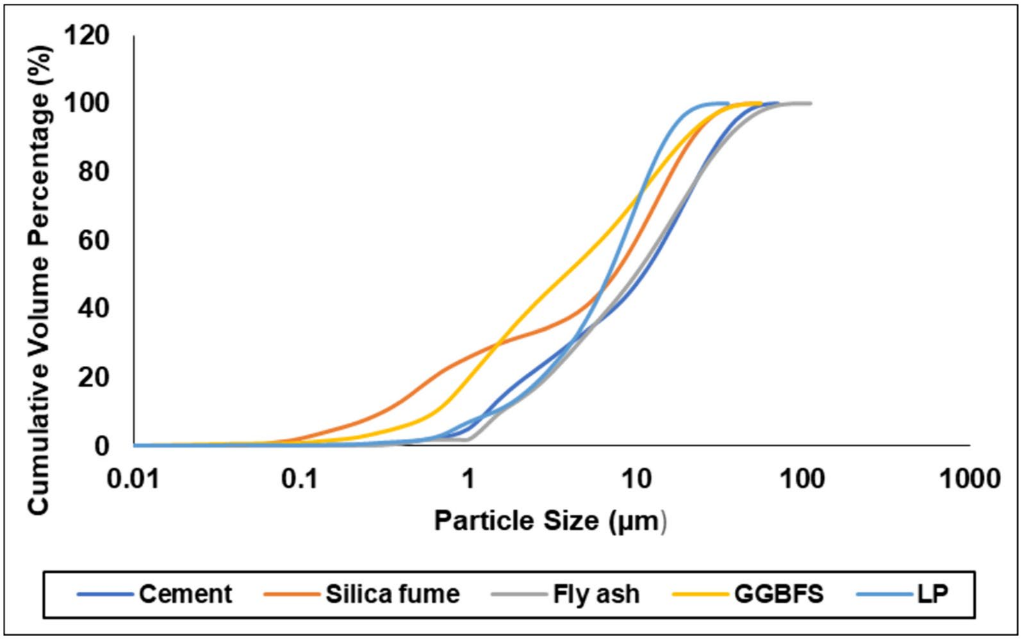


Fig. 1 Particle size distribution of Cement, SF, FA, GGBFS and LP

2.2 Mixture Proportioning

Two control UHPC mixtures were developed, one without GGBFS and another with GGBFS replacing 25% of cement both without LP. These two mixtures were modified by partially substituting cement with LP, with replacement levels ranging up to 20% by mass of cement, in order to ascertain the optimal LP dosage. This yielded a total of eight mixtures, which included the original two control mixtures. SF and FA were the other two SCM's employed in these mixtures, and their quantities remained the same for all eight mixtures.

FA was utilized to substitute a portion of the expensive SF, contributing to enhanced sustainability. Each mixture is designated with an alphanumeric code that indicates the presence of GGBFS and LP, along with their respective replacement percentages. For instance, the mixture C-S25-LP10 denotes a composition with cement © having 25% replaced by GGBFS (S25) and 10% replaced by LP (LP10). The mixture proportions of these eight mixtures are presented in Table 2.

Table 2 Mixture proportion of UHPC mixtures

Mixture	Cement kg/m^3	SF kg/m^3	GGBFS kg/m^3	FA kg/m^3	LP kg/m^3	Sand kg/m^3	Steel fibers kg/m^3	HRWRA l/m^3	Water kg/m^3	w/cm
UHPC mixtures without GGBFS										
C-S0-LP0	900	69	0	103	0	1095	120	44.5	160	0.15
C-S0-LP10	810	69	0	103	90	973	120	44.5	160	0.15
C-S0-LP15	765	69	0	103	135	920	120	44.5	160	0.15
C-S0-LP20	720	69	0	103	180	864	120	44.5	160	0.15
UHPC mixtures with GGBFS										
C-S25-LP0	675	69	225	103	0	1080	120	44.5	160	0.15
C-S25-LP10	608	69	225	103	68	985	120	44.5	160	0.15
C-S25-LP15	574	69	225	103	101	944	120	44.5	160	0.15
C-S25-LP20	540	69	225	103	135	903	120	44.5	160	0.15

2.3 Specimen Preparation and Curing

A vertical shaft mixer operating at a paddle speed of 38 rpm was employed to blend the components of UHPC. Initially, the sand and cementitious materials were combined in a dry state.

After dry mixing for 2 min, 75% of the total water content was introduced into the mixer.

Following thorough mixing, HRWRA was added and blended for an additional 5 min. Subsequently, the remaining 25% of water was added and mixed for an additional 5–6 min.

A visual examination was conducted to ensure there were no clumps of dry powder remaining. Following the visual inspection, the mixture was allowed to run for an additional minute before the fibers were introduced. Once the fibers were added, the mixture was set to run for another 4–5 min until it exhibited a workable and homogenous appearance. The overall mixing duration ranged from 15 to 20 min, and Fig. 2 illustrates the sequential mixing steps. Subsequently, the workability of the freshly mixed UHPC was assessed by conducting a flow table test in accordance with ASTM C1437. To examine the impact of curing conditions on UHPC properties, this research explored two distinct curing regimens, with the specifics of these regimens provided in Table 3.

2.4 Methods

2.4.1 Workability

The fresh UHPC was poured into the mold in two layers, with each layer being tamped 20 times. Following this, the top surface was smoothened. The mold was then lifted and immediately dropped onto the Table 25 times within a 15-s period. Subsequently, the diameter of the fresh sample was measured in two diametrically opposite directions, and the average flow was recorded and reported. This procedure is outlined in ASTM C1437 (ASTM, 2020).The test setup and the UHPC flow resulting from the test are shown in Fig. 3.

2.4.2 Compressive Strength

The compressive strength of UHPC was evaluated using 50 mm cubes according to ASTM C109 (ASTM C109, 2020) at seven and 28-days of curing. Figure 4 illustrates the compression testing for cube specimens.

2.4.3 Flexural Strength

Four prismatic specimens, each measuring 75 × 100x 400 mm were cast for each mixture and cured under MC and WB curing regimens for 28 days to evaluate the flexural behavior of UHPC mixtures. Figure 5 illustrates the test set up for flexural strength testing. Flexural strength

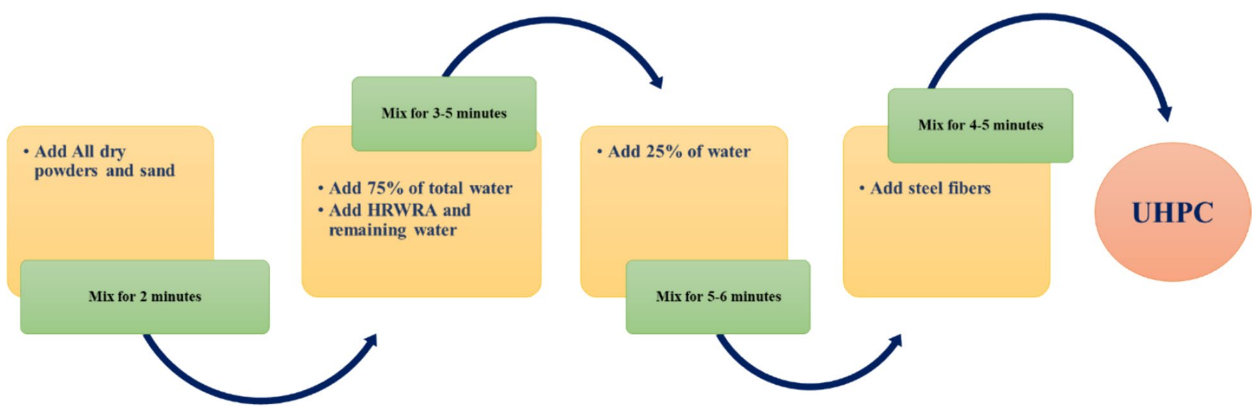


Fig. 2 Mixing procedure for UHPC

Table 3 Curing regimens used for compressive strength and modulus of rupture tests

Type	Designation	Specification
Moist curing	MC	The specimens were left in the mold for a period of 24 h. Following demolding, they were subsequently relocated to a curing room with controlled temperature and humidity conditions until testing
Warm bath curing	WB	The specimens were left in the molds for a period of 24 h. Following the demolding, the specimens were then subjected to curing in a water bath maintained at 90 °C until testing

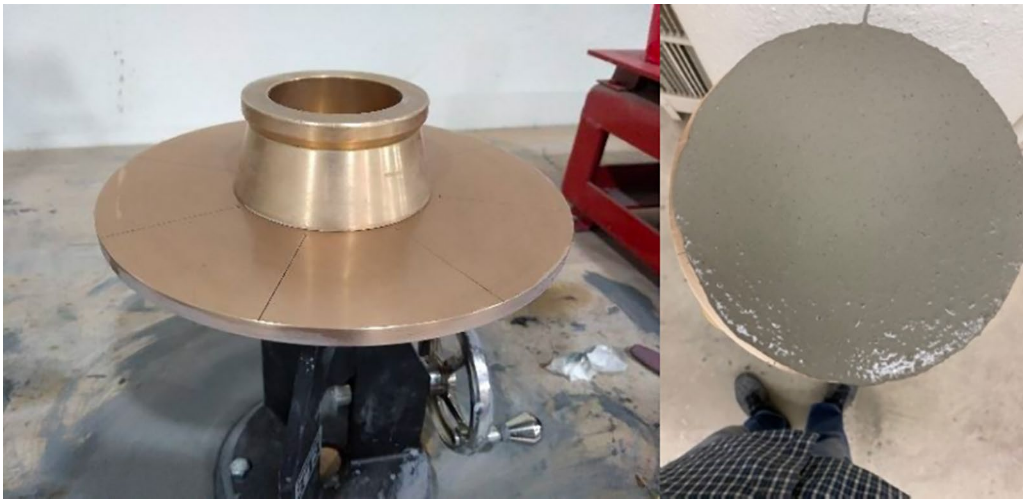


Fig. 3 Measuring flow of fresh UHPC

Fig. 4 Test setup for 2-inch cube compressive strength

testing was performed according to ASTM C1609 (ASTM, 2019).

From the test data, modulus of rupture (MOR) which is the first peak strength, peak stress, residual stress at L/600 and L/150 net deflections, where L is the effective length of the beam (305 mm), and toughness of UHPC mixtures were evaluated.

2.4.4 Drying and Autogenous Shrinkage

Two prismatic specimens, each measuring 75×75×285 mm were cast for each batch, with gauge studs inserted at the ends following ASTM C157 (ASTM C157, 2017), establishing a 250 mm effective length for shrinkage measurement. After casting, the specimens were left in the mold for 24 h before being demolded. Subsequently, they were submerged in lime-saturated water for half an hour prior to taking the initial measurements.

The initial length comparator readings were then recorded. The specimens were then placed in MC curing regimens for the next 2 days. After 2 days of curing, the specimens were left in the air at room temperature for the next 52 days. Length comparator readings were recorded every other day. The method for measuring autogenous shrinkage is similar to that of drying shrinkage with the exception that the specimens were covered with food-grade plastic wrap/aluminum foil after being saturated in lime water for 30 min to minimize the change in length due to change in temperature. Figure 6 depicts the experimental set up for shrinkage measurement.

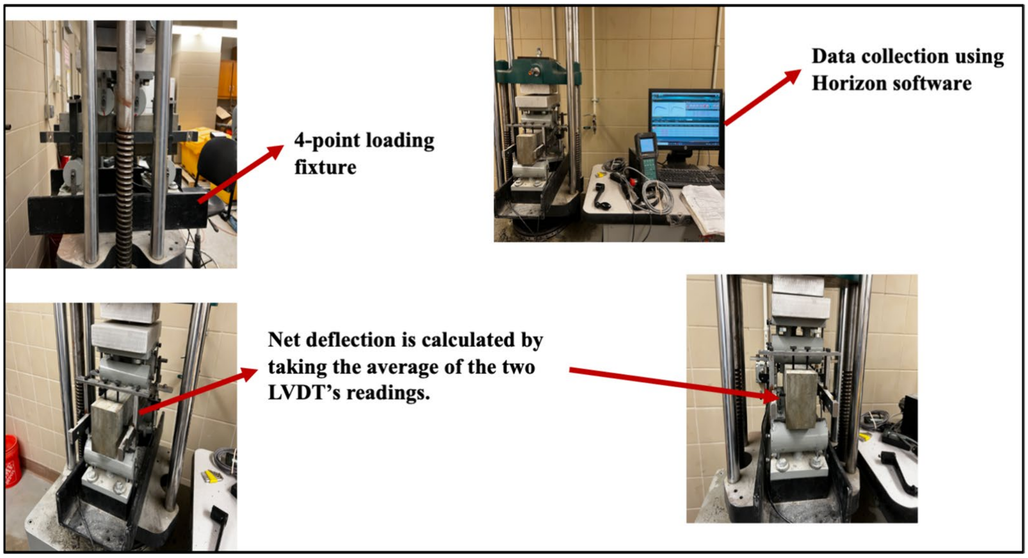


Fig. 5 Flexural strength test set up

Fig. 6 Drying and autogenous shrinkage samples (covered with aluminum foil to prevent moisture loss)

The value of shrinkage recorded on the 56th day is considered as the ultimate shrinkage for the UHPC mixtures. The average of two samples was reported as final shrinkage strain which was calculated using Eq. 1.

$$\Delta = (L_x - L_0)/10 \tag{1}$$

where L_x represents the length comparator reading on the test date and L_0 is the initial length comparator reading.

2.4.5 Cement Composition Index (CCI) and Clinker to Cement Ratio (CCR)

The CCI was calculated for the UHPC mixtures to determine the cement content required to give a unit compressive strength. Equation 2 was used to determine the CCI of the UHPC mixtures studied and compared with other studies.

$$CCI = \frac{Cement\ content\ \left(\frac{Kg}{m^3}\right)}{Maximum\ 28 - day\ compressive\ strength\ (MPa)} \tag{2}$$

A graph correlating the LP content and the CCI was generated to investigate the potential of replacing unhydrated cement, typically underutilized in UHPC, with LP as a means to enhance the sustainability of UHPC. Substituting cement with LP not only harnesses LP's filler properties to enhance the microstructure of UHPC but also diminishes environmental impact by reducing cement consumption. Similarly, the CCR, which indicates the ratio of cement present in the mixture to the total powder content (cement, SCMs, and LP) was computed for all the UHPC mixtures with different LP dosages using Eq. 3. This ratio serves as an indicator of the proportion of cement used in concrete production, thereby reflecting the amount of clinker required to produce the cement content of the mixture.

$$CCR = \frac{Mass\ of\ cement\ in\ the\ mixture}{Mass\ of\ (cement\ +\ SCMs\ +\ LP)} \tag{3}$$

3 Results and Discussion

3.1 Workability

The effect of LP on workability (flow) of UHPC mixtures produced with and without GGBFS was studied with LP dosage ranging from 0 to 20% (Fig. 7). The addition of GGBFS did not significantly influence the flow of UHPC mixtures at 0% LP dosage. This observation can be explained by the marginal decrease in workability when GGBFS is introduced. Specifically, the workability of the UHPC mixture without GGBFS and without LP was only 3.33% greater than that of the mixture with GGBFS. This slight reduction in workability can be attributed to the improved particle size distribution and enhanced particle packing brought about by the inclusion of GGBFS as a partial replacement for cement.

The enhanced particle packing leads to better interlocking of particles within the mixture. While this improves the density and mechanical properties of the UHPC, it restricts the relative movement of the particles, thereby impeding flow during mixing. This restriction in flow results in a slight decrease in the spread, as observed in the flow test (Wille et al., 2011, 2012). Therefore, while GGBFS does not drastically change the flow properties, the marginal decrease is due to the physical characteristics of the particle interactions within the UHPC matrix.

As can be seen from Fig. 7, LP plays a significant role in improving the workability of UHPC. The workability of UHPC mixtures with and without GGBFS was increased by 33% and 30%, respectively, when compared to the corresponding control mixtures (0% LP mixtures with and without GGBFS).

According to Li et al. (2020), LP can be considered as mineral plasticizer that enhances the flowability of UHPC. This plasticization effect results from the repulsion between the OH- groups localized on the Ca^{2+} surface of LP and its lower water absorption. Furthermore, Yang et al. (2020).

reported that incorporating LP as a partial substitute for cement can increase the flowability of UHPC, primarily due to the higher water-to-cement ratio resulting from the replacement of a portion of cement with LP. Furthermore, the workability of UHPC mixtures containing GGBFS was nearly identical to that of UHPC mixtures that did not incorporate GGBFS at any level of LP replacement.

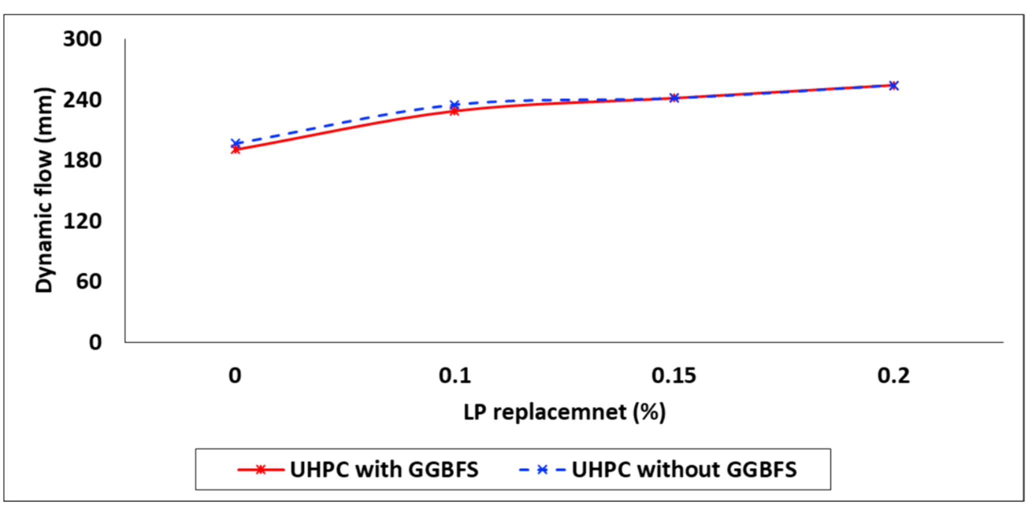


Fig. 7 Effect of LP dosage on workability of UHPC mixtures

3.2 Compressive Strength

Compressive strength testing was performed on 50 mm cube specimens as per ASTM C109 (ASTM C109, 2020) after seven and 28 days of curing. Figure 8 and Table 4 show the compressive strengths of UHPC mixtures after seven and 28 days. These mixtures were produced with and without GGBFS, cured under both MC and WB regimens, and included LP dosages ranging from 0 to 20% by mass of cement.

The early age (7-day) compressive strengths of UHPC mixtures with GGBFS without LP showed 9% and 5.5% lower compressive strength under MC and WB curing regimen, respectively, when compared with UHPC mixture without GGBFS and without LP (Fig. 8). The early age compressive strength for UHPC mixture without GGBFS was marginally lower compared to UHPC mixture without GGBFS. Addition of GGBFS tends to have lower early age strengths. But Prakash et al. (2022) compared the early age strength of binary mixture with cement and GGBFS and ternary mixture with cement, SF and GGBFS and reported that the reduction in early age compressive strength when GGBFS is used as cement replacement can be offset by incorporating SF due to the synergy between GGBFS and SF. The early strength

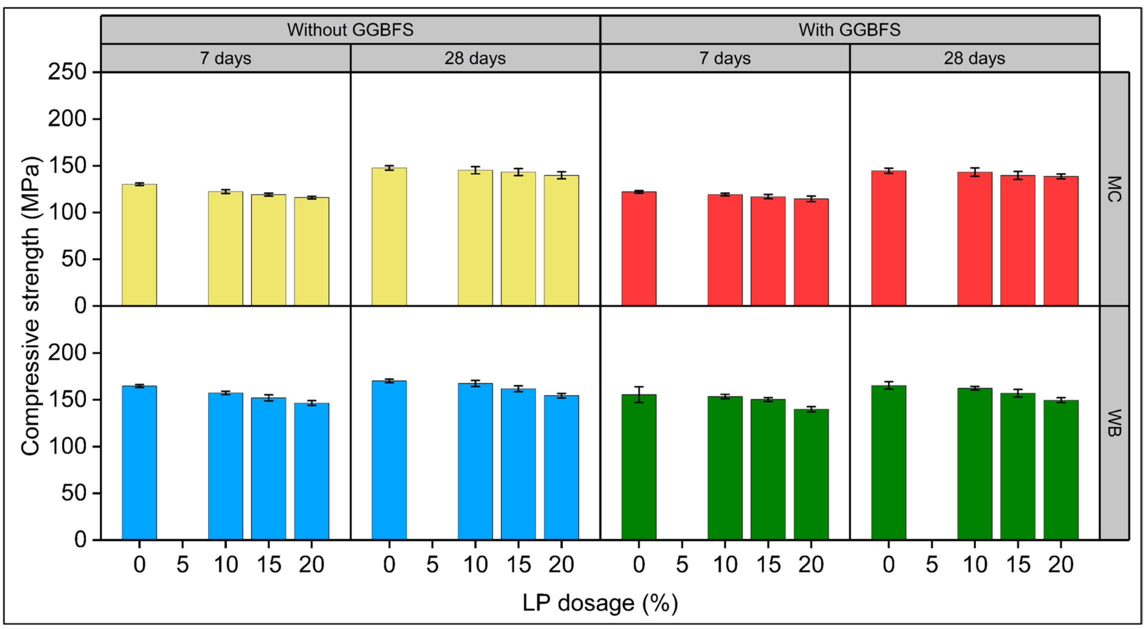


Fig. 8 Compressive strengths of UHPC mixtures without and with GGBFS and with LP dosages varying from 0 to 20% cured under MC and WB regimens for seven and 28-days

Table 4 Compressive strengths of UHPC mixtures without and with GGBFS and with LP dosages varying from 0 to 20% cured under MC and WB regimens for seven and 28-days

Curing regimen	LP (%)	With GGBFS		Without GGBFS	
		7-day compressive strength (MPa)	28-day compressive strength (MPa)	7-day compressive strength (MPa)	28-day compressive strength (MPa)
)MC	0	122	144	130	147
	10	119	143	122	145
	15	117	139	119	143
	20	114	138	116	139
WB	0	155	166	164	171
	10	153	162	157	168
	15	150	157	152	161
	20	139	149	146	154

development in ternary mixes can be attributed to the highly reactive nature of SF particles, which significantly accelerate the hydration process within the concrete mix (Prakash et al., 2022).

As depicted in Fig. 8, the compressive strengths of MC-cured UHPC mixtures without GGBFS decreased by 11% and 5% at seven and 28 days, respectively, when the LP dosage was increased to 20%. Similarly, the seven-day and 28-day compressive strengths of WB-cured specimens produced from these mixtures were decreased by 10.5% when the LP dosage was increased to 20% for both MC and WB curing regimen. The greatest 28-day compressive strength, which reached 171 MPa, was observed for the UHPC mixture without LP under the WB curing regimen. Among the LP replacement dosages, 10% LP replacement showed the greatest 28-day compressive strength of 168 MPa under the WB curing regimen.

In the case of UHPC mixtures containing GGBFS, the decrease in compressive strengths followed a similar trend to that of mixtures without GGBFS (Fig. 8). The seven day and 28-day compressive strengths of MC cured specimens were decreased by 6% and 4%, respectively when LP dosage was increased to 20%. The 7-day and 28-day compressive strengths of WB cured specimens decreased by 10%, when LP dosage was increased to 20%. The greatest 28-day compressive strength, which reached 166 MPa, was observed for the UHPC mixture with GGBFS and without LP under the WB curing regimen. Among the LP replacement dosages, 10% LP replacement showed the greatest 28-day compressive strength of 162 Mpa under the WB curing regimen. The decrease in compressive strength can be attributed to the increase in LP dosage, which leads to a reduction in the volume of cement. When incorporating LP into cementitious substances, the decrease in compressive strength arises from various physical mechanisms, including the dilution effect and filler effect (Bonavetti et al., 2003; Cyr et al., 2006). It is also significant to acknowledge that LP does not exhibit pozzolanic characteristics, which results in the absence of additional C–S–H gel formation. Consequently, increasing the LP content affecting the overall mechanical strength of UHPC.

Also, UHPC mixture without GGBFS performed better as compared to UHPC with GGBFS in both MC and WB curing regimens after 7 and 28-days (Fig. 8). This is because, UHPC with GGBFS has lower content of cement as compared to UHPC without GGBFS which leads to greater dilution effect when cement is further replaced with LP (Abdulkareem et al., 2018). Ding et al. (2021) reported that reducing the binder content in UHPC can delay its peak hydration time. They concluded that decreasing the binder quantity adversely affects cement hydration. This suggests that a volume decrease in binder content causes a dilution effect, which impacts both the availability of water and the space required for effective hydration.

The Bonferroni-Holm pairwise comparison test, which provides pairwise comparisons of the means of different groups, was conducted to determine significant differences between the mean compressive strengths of 0% and 10% LP P replacement for UHPC mixtures with and without GGBFS, considering 28-day compressive strength under MC and WB curing regimens (Table 5). From Table 5, it is evident that with 95% confidence, there is not statistically significant difference in compressive strengths between UHPC mixture with 0% LP and with 10% LP replacement, whether they contain GGBFS or not. Adding 10% LP as a cement replacement showed little to no effect on early mechanical strength (Bentz et al. 2017). It is also evident from Fig. 8 that UHPC mixtures produced with LP replacements greater than 10% were also exhibited UHPC -class compressive strengths (> 120 MPa). Further, to attain a compressive strength of 120 MPa, the need to cure the samples at elevated temperature for 28-day is not necessary since the compressive strength of 120 MPa can be achieved in 7 days of WB curing.

3.3 Flexural Strength

The key value of UHPC is not only its high compressive strength, but also its flexural performance. UHPC generally has superior flexural strength because of the addition of fibers and the strong bonding between the fibers and the matrix. The load–displacement curves of UHPC mixtures incorporated with LP ranging from 0

Table 5 Bonferroni-Holm comparison significance test for UHPC mixtures with and without GGBFS

UHPC mixture	LP % comparison		Curing regimen	*P*-value	Bonfferoni-Holm pairwise comparison test (Significance)
With GGBFS	0	10	MC	0.52778854	No
	0	10	WB	0.12615471	No
Without GGBFS	0	10	MC	0.20817027	No
	0	10	WB	0.10088269	No

to 20% under 28-days of MC and WB curing regimens are shown in Fig. 9 (with GGBFS) and Fig. 10 (without GGBFS).

3.3.1 Modulus of Rupture

Figure 11 shows the first cracking flexural strengths (MOR) of UHPC mixtures. It is evident that MOR

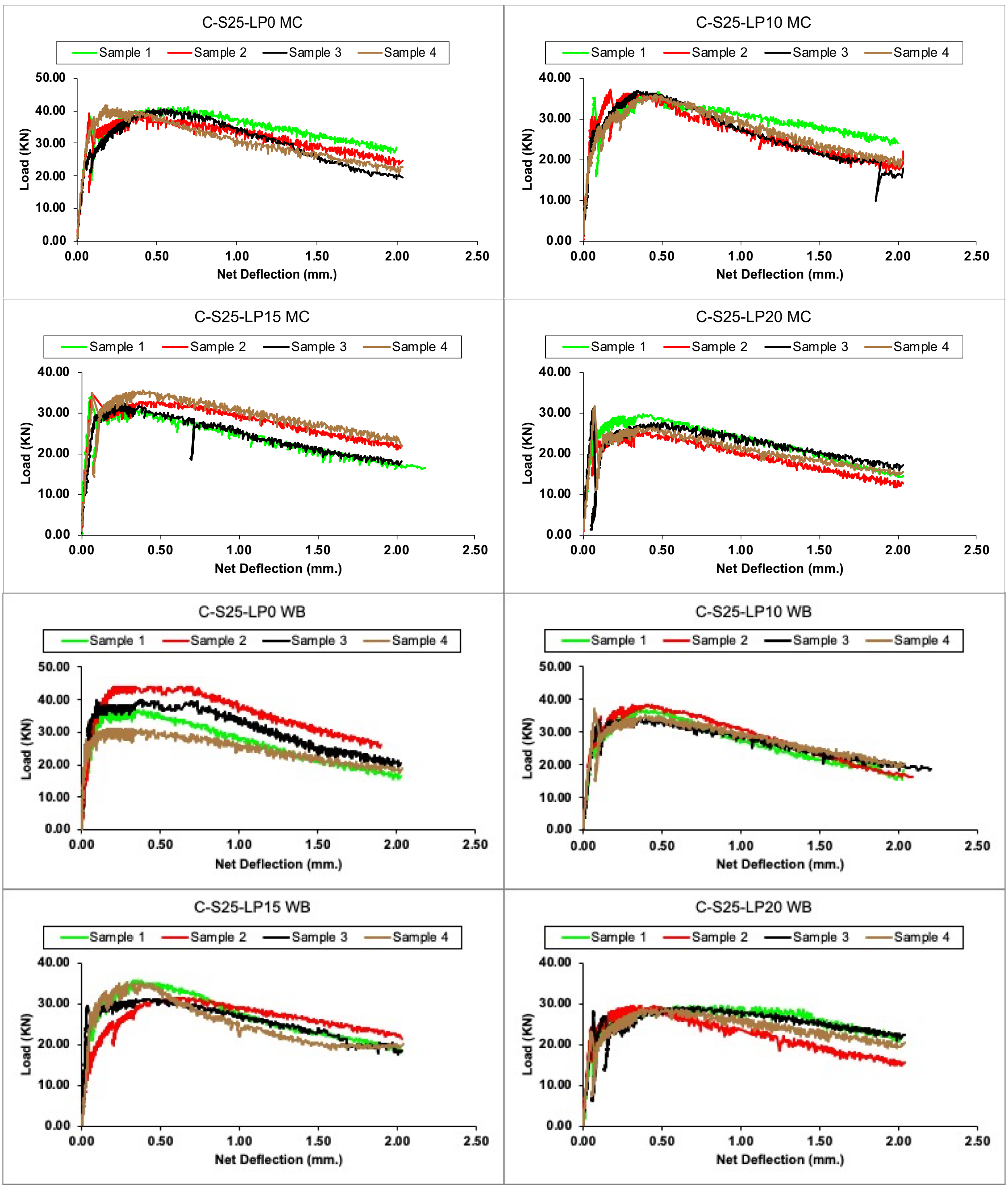


Fig. 9 Load versus net deflection curves for UHPC mixtures with GGBFS with LP 0–20%

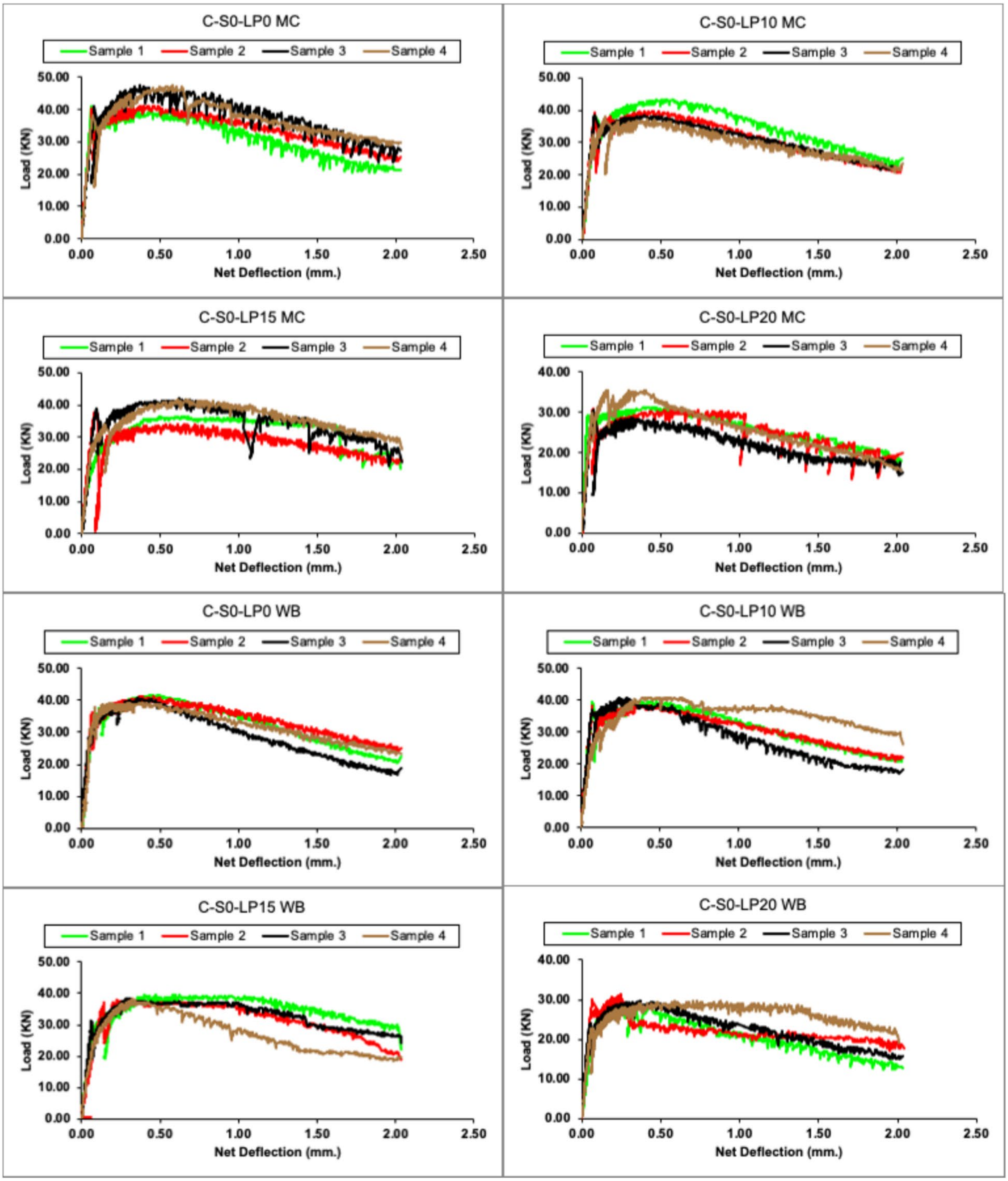


Fig. 10 Load versus net deflection curve for UHPC mixtures without GGBFS with LP 0–20%

decreased with the increase of LP% as a replacement of cement. The 28-day MOR values of MC and WB cured specimens decreased by 20% and 25% when LP dosage was increased to 20% for UHPC mixture with GGBFS. Similarly, 28-day MOR values of MC and WB cured specimens decreased by 30% when LP dosage was increased to 20% for UHPC mixture without GGBFS. The maximum MOR among the LP replacement

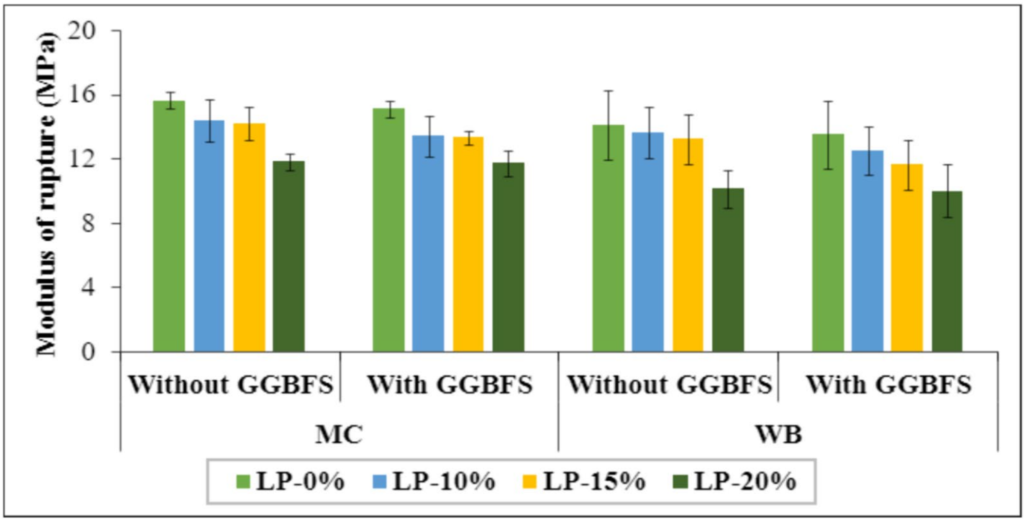


Fig. 11 First peak strength (MOR) for UHPC mixtures with and without GGBFS

dosages was observed for 10%, 14.4 and 13.4 MPa for with and without GGBFS UHPC mixtures, respectively, under MC curing regimen. MOR values followed the similar trend as observed in compressive strengths under MC and WB curing. When LP was used to replace cement, the decrease in the amount of cementitious materials in the UHPC mixture (dilution effect) resulted in a corresponding decrease in the flexural strength of UHPC mixtures.

3.3.2 Peak Flexural Strength

Figure 12 depicts the peak strengths of UHPC mixtures with varying LP dosage, both with and without GGBFS, under MC and WB curing regimens. It is important to observe the peak strength in the case of UHPC because the addition of fibers can help in achieving the strength even after the development of first crack. Steel fibers can effectively prevent the development and growth of cracks through its bridging and crack-restricting mechanisms further increasing the load carrying capacity even after first cracking (Zhang et al., 2023). A decrease in peak strength values was observed with an increase in LP dosage replacing cement up to 20%. The 28-day peak flexural strengths of both MC and WB cured specimens decreased by 26.5% when LP dosage was increased to 20% for UHPC with GGBFS. Similarly, 28-day peak flexural strength of MC and WB cured specimens decreased by 26% and 27% when LP dosage was increased to 20%

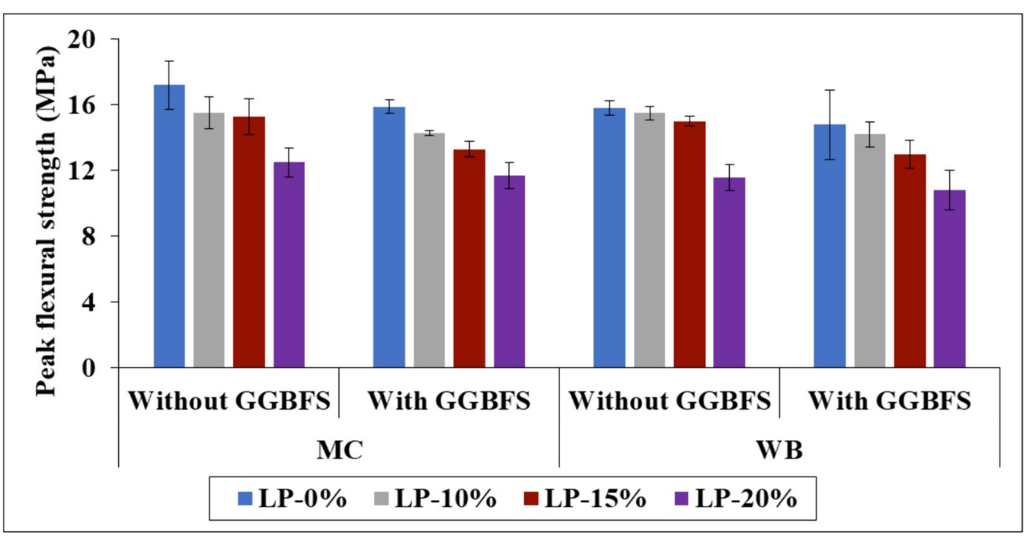


Fig. 12 Peak flexural strength for UHPC mixtures with and without GGBFS

for C-S0-LP, respectively. The maximum peak strength among the LP dosages was observed for 10%, 14.3, and 15.5 MPa for UHPC mixtures with and without GGBFS, respectively, under MC curing regimen.

3.3.3 Residual Flexural Strength

Furthermore, the residual flexural strengths of UHPC mixtures, both with and without GGBFS, were calculated at varying LP dosages and are depicted in Figs. 13 and 14 at deflections L/600 and L/150, respectively.

The residual strength at net deflections of L/600 and L/150 characterizes the residual capacity after crack formation. The residual strength at L/600 (Fig. 13) was decreased for UHPC with GGBFS when LP dosage was increased up to 20% by 31% and 28% under MC and WB curing regimen, respectively. For UHPC mixtures with

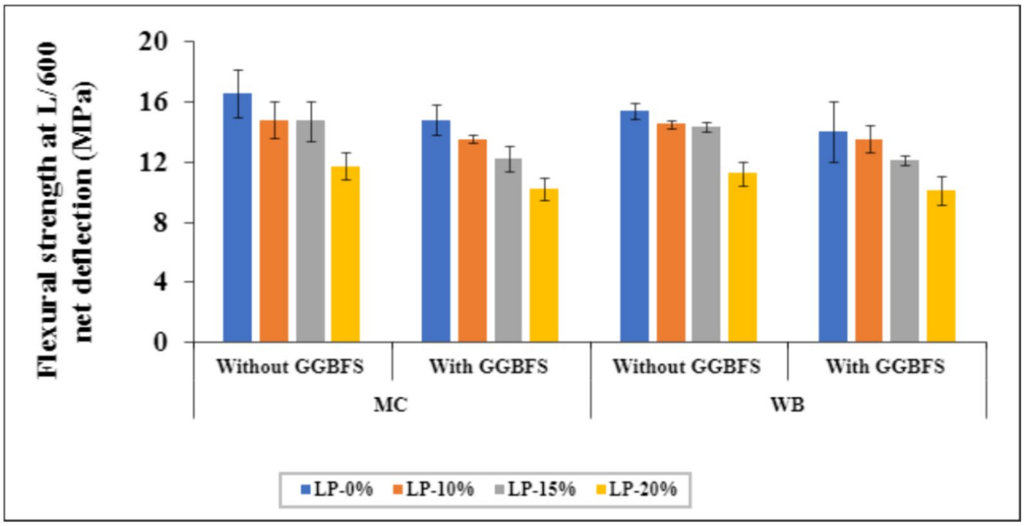


Fig. 13 Residual flexural strengths of UHPC mixtures with and without GGBFS at L/600 deflection

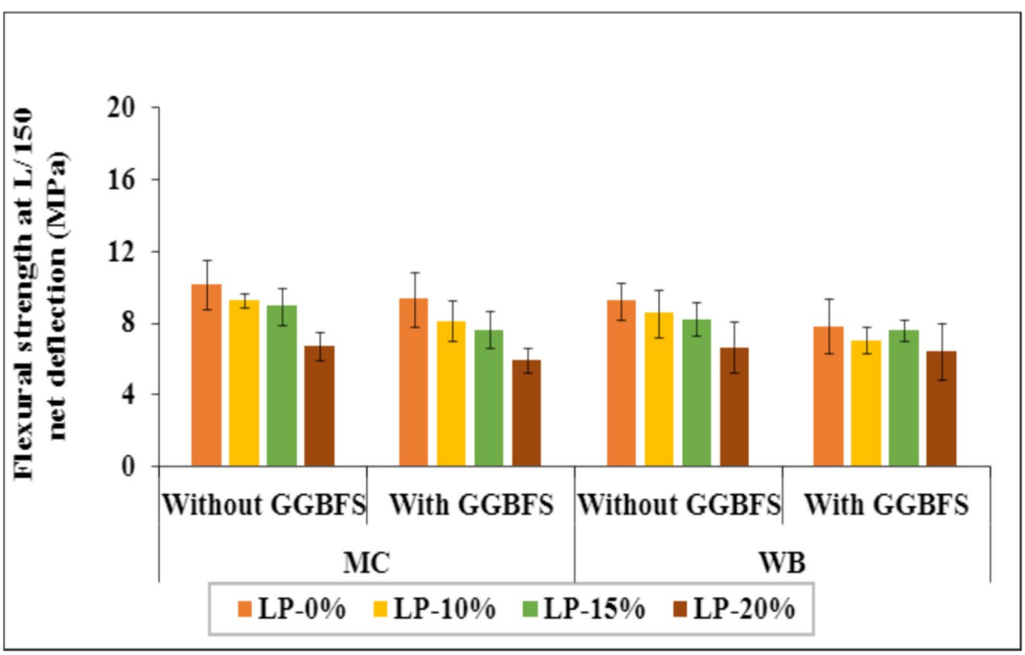


Fig. 14 Residual flexural strengths of UHPC mixtures with and without GGBFS at L/150 deflection

no GGBFS cured under MC and WB regimens, the residual strength at L/600 was decreased by 26.5%.

In the case of UHPC mixtures with GGBFS cured under MC and WB regimen, the residual strength at L/150 net deflection was decreased by 36% and 17% when the LP dosage was increased up to 20% (Fig. 14). The residual strength at L/150 net deflection for UHPC mixtures with no GGBFS, cured under MC and WB regimens was decreased by 33% and 28%, respectively, when LP dosage was increased to 20%.

3.3.4 Effect of WB Curing Regimen on Flexural Performance

It can be observed from the Figs. 11, 12, 13, and 14 that the MOR values, peak flexural strengths, and residual flexural strength of WB cured. The adverse effect of curing on flexural strength is more pronounced as larger sized specimens are more susceptible to steep temperature gradients during heat curing, as reported by Hu et al. (2021). Similar observations related to effect of curing on flexural strength has been reported by Tautanji et al. (1999) who concluded that addition of silica fume can induce more micro-shrinkage cracking as a result of which curing has a greater effect on flexural strength than on compressive strength.

Additionally, it can be observed that for all the LP dosages, the UHPC mixtures with GGBFS produced similar or lower flexural strength compared to UHPC mixtures without GGBFS (Figs. 11, 12, 13, and 14). Ahmad et al. (2021) and Shi et al. (2021) reported the negative effect of GGBFS on flexural strength. In addition to the dilution effect, reducing the cement content in UHPC results in fewer hydration products, diminishing the chemical influence of the binder materials (Shi et al., 2021). Although UHPC with reduced cement content shows lower porosity compared to traditional UHPC, the decrease in hydration product formation is likely responsible for the observed decline in both flexural and tensile properties (Shi et al., 2021).

In conclusion, the addition of LP to UHPC reduces its flexural strength. Similar results of decreased flexural strength with increase in LP dosage were seen in a study by Singniao et al. (2020) and Tayeh et al. (2022). However, the fibers in UHPC can bridge the cracks and carry the applied load further.

3.4 Toughness

The area under load versus net deflection curve up to net deflection of L/150 was determined to calculate the toughness of UHPC. Figure 15a, b shows the average toughness values for UHPC mixtures with and without GGBFS, with LP dosage varying from 0 to 20%. As can be seen from Fig. 15a, b, the toughness of UHPC mixtures cured under MC and WB regimens with GGBFS decreased by 30% and 31%, respectively, as LP dosage was increased 20%. Similarly, for UHPC without GGBFS cured under MC and WB, the toughness was decreased by 28%. UHPC specimens cured under MC regimen exhibited greater toughness as compared to those cured under WB regimen. The greatest toughness values were observed in UHPC mixtures containing LP replacing 10% of cement and these values for UHPC mixtures with and without GGBFS were 106 and 118 kN.mm, respectively. Overall, the results suggest that the use of LP as a replacement for cement beyond 10% in UHPC can have a negative impact on flexural toughness as seen in case of compressive and flexural strengths.

3.5 Effect of LP Content on Autogenous and Drying Shrinkage of UHPC

Two potential forms of shrinkage are drying shrinkage that occurs due to moisture loss from the UHPC, while autogenous shrinkage results from a volume reduction as the cementitious materials undergo hydration. Both drying and autogenous shrinkage were measured up to 56 days. Figures 16 and 17 show the average autogenous shrinkage and drying shrinkage for UHPC mixtures with and without GGBFS. From Fig. 16a, b, there was 31% and 40% reduction in autogenous shrinkage at 28 days for the UHPC with and without GGBFS UHPC mixture, respectively, with the 20%LP dosage. At 56 days, the autogenous shrinkage was decreased by 28% and 30% for with and without GGBFS UHPC mixture, respectively, with 20% LP dosage. When cement is replaced with LP, the dormant period is shortened due to the filler effect and the hydration of cement is accelerated which eventually reduced the autogenous shrinkage (Kang et al., 2019b).

Similar trend was observed in case of drying shrinkage (Fig. 17a, b). At 28 day, the drying shrinkage was decreased by 35% and 32% for UHPC mixtures with and without GGBFS, respectively, with 20% LP dosage. Similarly, at 56-day, the drying shrinkage was decreased by 28% and 22% for UHPC mixtures with and without, respectively, with 20% LP dosage. It is evident that with the increase in LP replacement percentage, both autogenous and drying shrinkages were decreased.

The reduction in overall shrinkage due to addition of LP can be attributed to the formation of the knee point at which the rate of increase in shrinkage begins to suddenly decelerate. The development of a stress-resistant microstructure at the knee point prompts the cessation of early-age shrinkage, and the earlier this point forms, the shorter the duration of rapid shrinkage, leading to a decrease in both initial and final shrinkage values (Kang et al., 2019; Mounanga et al., 2006). As the LP dosage increases from 0 to 20%, the formation of the knee point occurs earlier (Figs. 16 and 17).

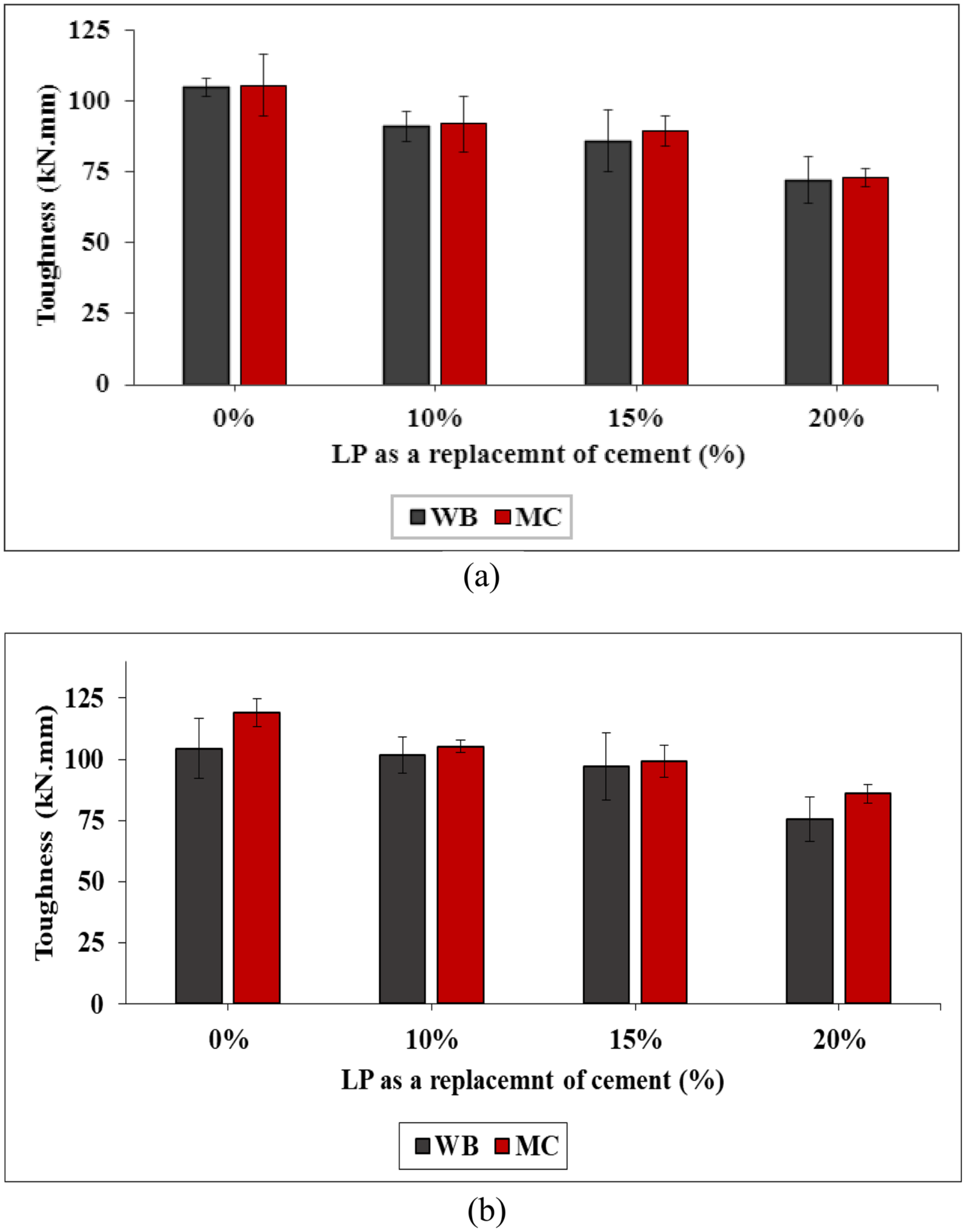
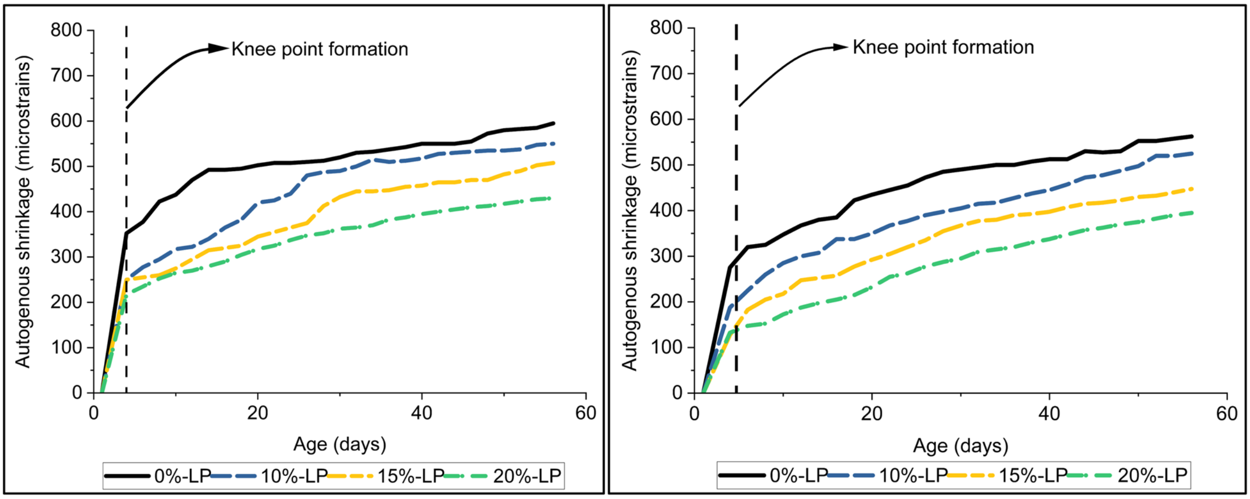


Fig. 15 Toughness values of UHPC mixtures **a** with GGBFS and **b** without GGBFS

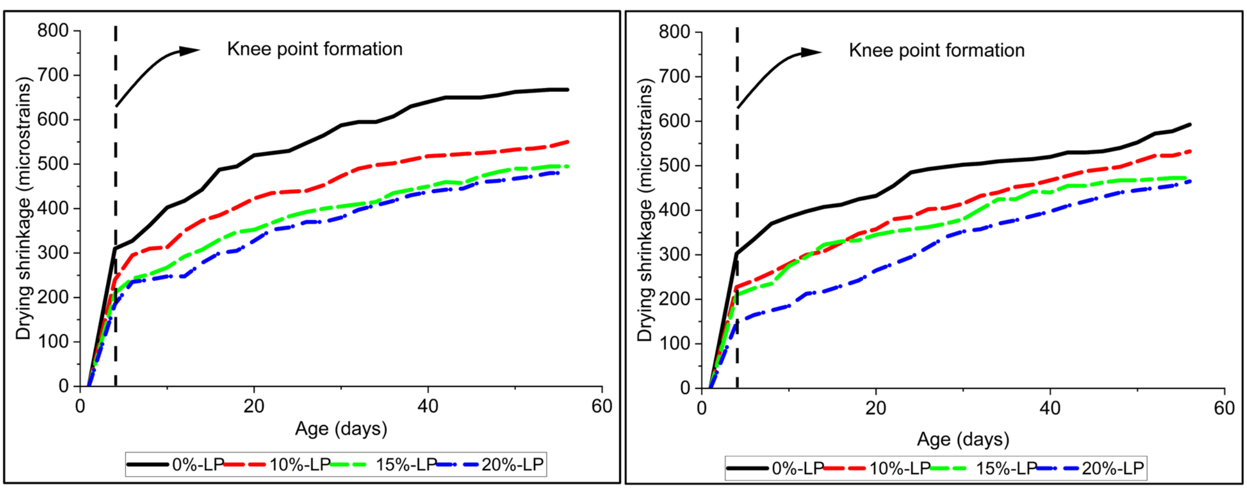
This underscores the significance of not just minimizing cement content but also ensuring the timely establishment of the knee point in influencing overall shrinkage values (Kang et al., 2019). Moreover, reduced overall shrinkage due to inclusion of 20% LP is a result of the reduction in absolute water content associated with higher levels of limestone powder. Consequently, this contributes to the enhancement of volumetric stability in UHPC (Zhang et al., 2016). Similar results were reported by Li.et al. (2020).

Based on Figs. 16 and 17, it is evident that while increasing the dosage of LP led to a reduction in shrinkage, the autogenous and drying shrinkage values were still higher in UHPC mixtures containing GGBFS. The addition of GGBFS significantly influenced the increase in shrinkage, mainly due to its ability to refine the pore structure



(a) (b)

Fig. 16 Autogenous shrinkage of UHPC mixtures **a** with GGBFS and **b** without GGBFS



(a) (b)

Fig. 17 Drying shrinkage for UHPC mixture **a** with GGBFS and **b** without GGBFS

of the concrete. This refined pore structure caused more pronounced shrinkage effects, as indicated by the higher shrinkage values in the mixtures with GGBFS (Lim and Wee, 2000; Yalcinkaya and Yazici, 2017).

4 Sustainability

UHPC has the ability to achieve about 4–8 times strength compared to normal concrete while using about 2–4 times more cement per unit volume. In addition, its exceptional durability stands out as a key factor contributing to its longevity. For example, as the need to renovate or refit old concrete structures increases, the use of UHPC in the form of thin liners (typically 30–40 mm thick) will provide significant improvements to the integrity of the concrete and function of the structure (Kang et al., 2019b). This can be achieved without placing a noticeable load on the weight of the structure (Kang et al., 2018; Brühwiler and Denarié, 2013). Furthermore, by increasing the thickness of the UHPC by a few millimeters, the service life of the concrete structure can be extended by decades. Such measures enhance the sustainability of the construction. Widespread adoption of UHPC for repair and restoration purposes has the potential to reduce portland cement consumption associated with the construction of new structures. In addition, it can play an important role in reducing environmental problems such as the generation of fine dust and waste during the demolition of structures.

The addition of LP can reduce the amount of unhydrated cement which is not being used in its original form. Hence, LP can be a useful substitute to reduce the cement in UHPC and to improve sustainability. To evaluate this, CCI which is used to access the efficiency of cement consumed in self-compacting concrete (Pelisser et al., 2018) serves as a crucial metric for gauging the effectiveness of cement utilization in the given context. This study was also conducted by Kang et al. (2019b) to measure the cement efficiency in UHPC. CCI implies the amount of cement content (in kg/m^3) needed to achieve a unit compressive strength of 1 MPa. A lower CCI value indicates a more efficient consumption of cement for producing a specific volume of concrete, as a smaller quantity of cement is incorporated in the concrete to attain the desired strength level. Figure 18 shows the CCI as a function of LP content in various formulations of UHPC reported by Yu et al. (2015), Kang et al. (2019), and Huang et al. (2017) comparing with the UHPC formulations developed in the current study. It can be observed that CCI proportionally decreases with the increase in LP content (Fig. 18). In the UHPC mixtures presented in the current study, for instance, the UHPC mixture with GGBFS requires 4 kg of cement to achieve 1 MPa strength when no LP is used to replace cement. Similarly, for the UHPC mixture without GGBFS, 5.3 kg of cement is needed to attain 1 MPa strength when no LP is used as a replacement. When LP is used as replacement of cement in UHPC mixture with GGBFS, the amount of cement used was 10% less as compared to UHPC mixture with GGBFS when no LP is used as cement replacement. It can be noted that this decrease in cement content is calculated after 25% of cement has been replaced with GGBFS.

Similarly, for UHPC mixture without GGBFS, the amount of cement used was 13% less as compared to UHPC mixture with and without GGBFS when no LP is used as cement replacement. As the LP replacement is increased, the CCI ratio decreases for both types of UHPC mixtures. This study shows that using LP to replace cement in UHPC can reduce the amount of cement needed to achieve the desired strength, even though the mechanical strength may be affected marginally due to the cement dilution effect, as discussed in previous sections. Therefore, decreasing the amount of unhydrated cement in low w/cm ratio concretes by replacing it with LP is a rational approach from both environmental and economic perspectives.

Another sustainable way to produce concrete is to reduce the CCR by using SCMs effectively (Gupta &

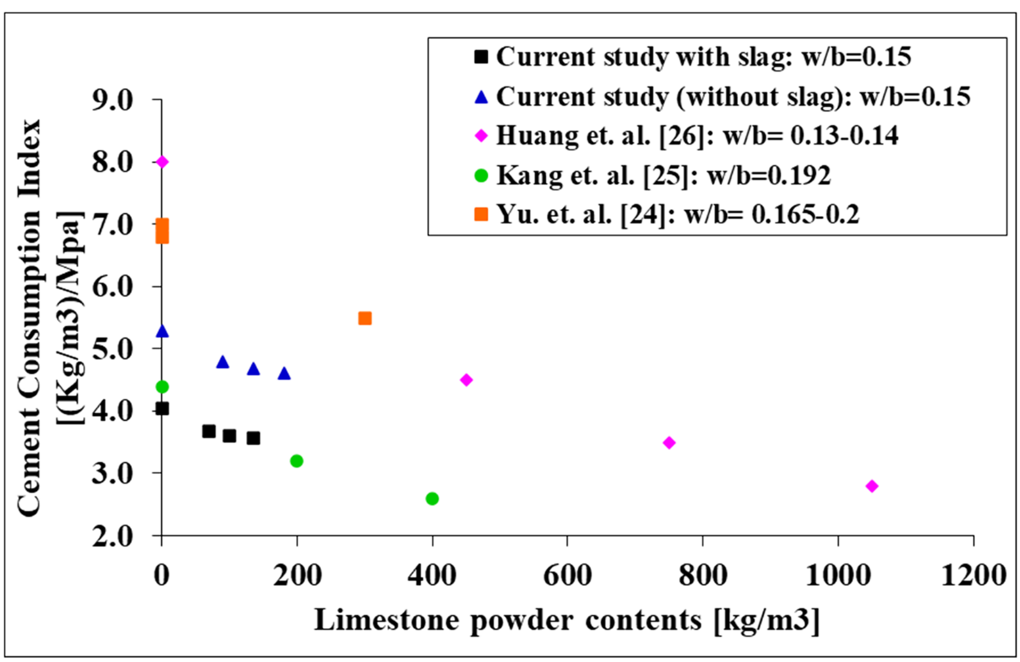


Fig. 18 Comparison of cement consumption index of UHPC mixtures developed in this study with other studies

Table 6 CCR values for all the UHPC mixtures presented in the current study

UHPC mixture	CCR values
C-S25-LP0	0.63
C-S25-LP10	0.57
C-S25-LP15	0.54
C-S25-LP20	0.50
C-LP0	0.84
C-LP10	0.76
C-LP15	0.71
C-LP20	0.67

Chaudhary, 2022; Singh et al., 2020). According to UN Climate Technology Centre and Network (U.N, 2022), the average CCR is about 0.81. This ratio is with the adjustment comprising gypsum and added substances such as GGBFS, FA, and natural pozzolans. Table 6 shows the various CCR values for all the mixtures used in this study.

The lowest CCR is for the UHPC mixture with GGBFS. In comparison with UHPC mixture without GGBFS, the CCR of UHPC with GGBFS was 25% lower. This is approximately 40% less in comparison with the average global CCR value. Similarly, for UHPC mixture without GGBFS, after 20% cement replacement of cement with LP, the CCR was 0.67, which is approximately 20% lower than the global average CCR. Use of 20% LP as a replacement of cement with the incorporation of GGBFS can help in producing UHPC with improved workability, comparable mechanical performance and reduced shrinkage besides reducing the cement content by half.

Therefore, incorporation of various SCM's with LP can be used to produce eco-friendly and cost-effective UHPC.

5 Conclusions

1. As the limestone powder (LP) content increased, workability in UHPC showed improvement, reaching a 30% increase for mixtures with GGBFS and a 33% increase for those without GGBFS at a 20% LP dosage.
2. The compressive strength of UHPC mixtures decreased with an increase in LP dosage up to 20%. However, no significant reduction in compressive strengths of UHPC mixtures was observed at a 10% LP dosage. Overall, a 20% LP replacement can produce UHPC-class compressive strengths under both standard and accelerated curing regimens.
3. LP replacement negatively affected the flexural performance of UHPC, as evidenced by the decline in the 28-day modulus of rupture, peak flexural strength, and residual strength, all showing a consistent trend with increased LP dosage.
4. The flexural strengths of WB cured specimens were lower than those cured under MC regimen.
5. Incorporation of LP led to a reduction in both autogenous and drying shrinkage of UHPC mixtures. Using 20% LP, there was 28% and 30% reduction in autogenous shrinkage in UHPC mixtures with and without GGBFS, respectively, after 56 days. Similarly, 29% and 21.5% reduction in drying shrinkage was observed in UHPC mixtures with and without GGBFS, respectively, after 56 days.
6. The study evaluated the cement composition index (CCI) to assess the efficiency of cement consumption. The data showed that CCI decreased as LP content increased. For UHPC mixture with GGBFS, 20% LP replacement resulted in a 10% decrease in CCI compared to UHPC mixture without GGBFS.
7. Cement-to-clinker ratios (CCR) were calculated for UHPC mixtures. The greatest reduction of CCR value was observed in UHPC mixture with GGBFS. This was 40% lower than the global average value of 0.81.

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Author contributions
YS conducted laboratory investigation, data curation, data analysis, and was a major contributor in writing the original draft preparation, MY contributed to laboratory investigation and data curation, SA was responsible for conceptualization, data analysis, review and editing of the manuscript, and overall supervision of the research. JO contributed to the review and editing of the manuscript.

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Declarations

Competing interests
No competing interests.

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