A Study on the Reduction of Water Loss and Shrinkage of Concrete Pavements by Using Finely Ground Blast Furnace Slag (GGBFS) Combined with Lightweight and Coarse Sand

Thai-Binh Le
Faculty of Mechanical Automotive and Civil Engineering, Electric Power University, Hanoi, Vietnam
Binhlt@epu.edu.vn

Viet-Thuc Chu
Department of Research Management and International Cooperation, Electric Power University, Hanoi, Vietnam
Thuccv@epu.edu.vn (corresponding author)

Van-Chinh Nguyen
Faculty of Mechanical Automotive and Civil Engineering, Electric Power University, Hanoi, Vietnam
Chinhnv@epu.edu.vn

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ABSTRACT

This study investigates water loss and shrinkage in cement concrete, utilizing Ground Granulated Blast Furnace Slag (GGBFS) and a combination of Lightweight Sand (LS) and Coarse Sand (CS) as admixtures under hot-humid conditions. The study evaluates the effects of GGBFS, and LS and CS on reducing shrinkage and improving moisture retention. Standard concrete mixtures were prepared and tested under controlled and outdoor conditions with different combinations of GGBFS, LS, and CS. Water loss and plastic shrinkage were measured during the first hours of casting, followed by drying shrinkage evaluations up to 90 days. The results indicate that GGBFS significantly decreased water loss during curing, improved aggregate packing density, and reduced plastic shrinkage compared with control mixtures. At later ages, mixtures with GGBFS, and LS and CS demonstrated lower drying shrinkage and enhanced dimensional stability. These findings provide practical insights for internally cured concrete, with direct application to cement concrete pavements. The novelty of this work lies in combining GGBFS with LS and CS under tropical hot-humid conditions.

Keywords-concrete shrinkage; ground granulated blast furnace slag; internal curing concrete; lightweight sand; coarse sand

I. INTRODUCTION

Concrete is required in transport infrastructure, especially in pavement construction that endures heavy traffic and harsh climates. However, early-age moisture loss remains a persistent problem caused by temperature, humidity, wind, and solar radiation, leading to shrinkage within hours of mixing. In hot and humid climates, inadequate curing accelerates this process, resulting in severe early deformation [1]. Improper curing increases water loss, plastic shrinkage, and reduces durability. In contrast, effective curing delays evaporation and enhances long-term performance [2]. Moreover, solar radiation intensifies evaporation and cracking. Conventional predictive models underestimate the radiation effects, highlighting the need for improved curing and modeling approaches [3].

Plastic shrinkage occurs before sufficient tensile strength develops, with strains between 2.0 and 2.85 mm/m in hot, arid regions, leading to surface cracking and reduced durability. In [4], a field study was performed in the dry region of Adrar, Algeria, and revealed that outdoor cracks developed faster than in laboratories. In addition, the use of admixtures reduced crack dimensions by 50-66% and product curing provided additional protection. Authors in [5] proposed limiting placement temperature to 35 °C to reduce such risks. Experimental studies on Ordinary Portland Cement (OPC) mixtures with different Water-Cement (W/C) ratios, ranging from 0.3 to 0.45, and curing methods concluded that shrinkage is minimized and strength maximized when placed around 32 °C. Additionally, higher W/C ratios increased shrinkage and reduced strength. Authors in [6] revealed that water-based curing compounds are the most effective, and wet burlap improves long-term strength. Furthermore, authors in [7] confirmed that curing compounds consistently minimized shrinkage across various binders, with optimal performance between 32 and 38 °C. These findings highlight the combined role of climate, mix design, and curing in controlling shrinkage and enhancing pavement performance.

Although shrinkage mechanisms have been examined, research in tropical regions, particularly in Vietnam, is limited. Incorporating GGBFS with limestone or lightweight aggregates has proven effective in retaining moisture, reducing shrinkage, and enhancing the durability of concrete in ternary blend systems [8]. Authors in [9] revealed that the use of GGBFS in concrete reduced shrinkage, enhanced strength, and improved water resistance, especially under hot and humid conditions. Furthermore, GGBFS enhances the mechanical properties of concrete [10]. Authors in [11] indicated that increasing the GGBFS content under heat-curing protocols reduces drying shrinkage and mortar. Additionally, in high performance concretes, GGBFS suppresses shrinkage strain [12]. GGBFS combined with lightweight aggregates also increases the durability of concrete [13]. LS and superabsorbent polymers maintain internal humidity, refine pore structure, and improve resistance to chloride ingress and frost damage [14]. Moreover, authors in [15] showed that replacing quartz sand with 100% saturated recycled Fine Aggregates (FA) reduces autogenous shrinkage by 90% and increases 28-day strength by 16%.

Concrete pavements are highly vulnerable to early-age water loss and shrinkage, particularly under hot-humid conditions. While previous studies have investigated factors, such as W/C ratio, curing methods, and mineral admixtures like GGBFS or lightweight aggregates, they are not focused on tropical climates such as that of Vietnam. Furthermore, the combined effect of GGBFS with LS and CS has not been systematically explored. Consequently, the present study aims to address this gap by evaluating their synergy in reducing water loss, mitigating shrinkage, and enhancing the durability of concrete pavements.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

The Nghi Son PCB40 cement is used, meeting the technical requirements presented in [16], with its properties outlined in Table I.

TABLE I. PHYSICAL AND MECHANICAL PROPERTIES OF NGHI SON PCB40 CEMENT

No.	Property		Value
1	Specific gravity (g/cm3)		3.10
2	Residue on 0.09 mm sieve (%)		1.8
3	Standard consistency (%)		28.0
4	Volume stability (mm)		1.0
5	Initial setting time (min)		132
	Final setting time (min)		195
6	At 3 days	Flexural strength (N/mm2)	6.4
		Compressive strength (N/mm2)	30.5
	At 28 days	Flexural strength (N/mm2)	8.3
		Compressive strength (N/mm2)	49.8

GGBFS is a byproduct of steel production and enhances concrete's mechanical and chemical properties. In addition, it improves water retention, maintaining moisture during curing. GGBFS can partially replace cement without sacrificing quality, enhancing concrete’s durability and resistance to environmental stresses. Furthermore, the GGBFS used in this study is sourced from Thainguyen Province, adhering to the Vietnamese standard TCVN 11586:2016 for granulated blast furnace slag powder used in concrete and mortar [17]. The slag is rapidly cooled from 1400-1500 °C to 30-40 °C, forming a white granular mixture with a particle size of less than 5 mm. In turn, the mixture is dried and ground in a vibrating ball mill to achieve a fineness of 6300 cm²/g. The chemical composition, particle size distribution, and physical properties of the GGBFS are presented in Table II, with its specific gravity being 2.94 g/cm^3.

TABLE II. MIX PROPORTIONS OF CEMENT-GGBFS MIXTURES

No.	GGBFS (g)	Cement (g)	Sand (g)	Water (g)	W/C	Workability (mm)	R7 (N/mm^2)	Activity Index I (%)
1	0	550	1512.5	236.5	0.43	107	52.6	100
2	50	450	1512.5	220.0	0.40	110	55.9	106

The FAs used in this study are a blend of keramzit LS and CS from the Lo River, Viet Tri. Both materials are dried and sieved to remove particles over 5 mm, with their properties listed in Table V. Table III presents the particle size distribution of the FA, as per [18].

LS and CS are mixed at replacement ratios of 10%, 20%, 30%, 40%, and 50%, with the results shown in Table IV, as per [18]. The optimal mix was found at a 30% CS-30% LS ratio, which was selected for further studying the concrete and internally cured concrete properties.

TABLE III. PARTICLE SIZE DISTRIBUTION OF LS AND CS

Sieve size (mm)	Retained cumulative mass (%)	
	Lightweight sand (CS) (%)	Coarse sand (LS) (%)
5	0	0
2.5	5.8	8.5
1.25	50.9	22.6
0.63	49.7	50.7
0.315	74.4	87.5
0.14	88.6	97.3

TABLE IV. PARTICLE SIZE DISTRIBUTION OF LS-CS MIXTURE

Sieve size (mm)	Cumulative mass retained, % mass				
	0.10 CS and 0.9LS	0.20 CS and 0.8 LS	0.30 CS and 0.7 LS	0.40 CS and 0.6 LS	0.50 CS and 0.5 LS
5	0	0	0	0	0
2.5	8.2	8.0	7.7	7.4	7.2
1.25	25.4	28.3	31.1	33.9	36.8
0.63	50.6	50.5	50.4	50.3	50.2
0.315	86.2	84.9	83.6	82.3	81.0
0.14	96.4	95.6	94.7	93.8	93.0

TABLE V. PHYSICAL AND MECHANICAL PROPERTIES OF CS AND LS

No.	Property	CS	LS	Mixture of CS and LS
1	Specific gravity (g/cm^3)	2.67	1.88	2.43
2	Saturated surface dry bulk density (g/cm^3)	2.64	1.71	2.36
3	Dry bulk density (g/cm^3)	2.63	1.52	2.10
4	Loose bulk density (Kg/m^3)	1410	930	1270
5	Water absorption (%)	0.7	14.1	4.8
6	Void content (%)	46.4	38.8	39.5
7	Particles larger than 5 mm (%)	0	0	0
8	Clay content (%)	0.7	1.9	1.1
9	Organic impurities (compared to standard color)	Lighter	Lighter	Lighter
10	Fineness modulus	2.7	2.7	2.7

The coarse aggregate selected for this study is crushed stone with a maximum particle size of 20 mm, sourced from the Jianxi limestone mine in Henan Province. Prior to its utilization, the crushed stone is cleaned and dried. The admixture used is a polycarboxylate-based superplasticizer from BASF, branded as MasterGlenium SKY 8588.

B. Experimental Methods

Concrete water loss and shrinkage are evaluated on standard samples of 100×100×400 mm, with an exposure modulus (Mh) equal to 30 m^{-1} under controlled conditions. Continuous shrinkage monitoring is challenging due to the lack of methods for recording before concrete hardening. In many cases, structures are demolded just one day after concrete casting, while large surfaces are still exposed to rapid drying and early shrinkage. To examine the influence of climate on water loss and shrinkage, three mixtures are tested and described in Table VI.

TABLE VI. MIXTURE PROPORTIONS OF CONCRETE

Mixture	Cement (kg/m^3)	GGBFS (kg/m^3)	Water (kg/m^3)	LS (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Admixture (kg/m^3)
CP1	299	0	135	249	581	1146	2,69
CP2	299	105	136	223	521	1147	2,69
CP3	297	--	135	--	900	1140	2.67

C. Experimental Equipment and Procedure

The experimental setup depicted in Figure 1 and the procedure for measuring the shrinkage and water loss of concrete mixtures were carried out in accordance with [19]. Minor modifications were applied to suit early-age monitoring. The setup consisted of 100×100×400 mm concrete specimens fitted with steel end plates. On the steel plates, high-precision dial gauges of 0.001 m resolution were directly mounted to record longitudinal deformation. Furthermore, the samples were placed on a flat, stable support, allowing free axial movement to minimize external restraint. An electronic balance with an accuracy of ± 0.01 g was used to determine the mass changes for water-loss evaluation. Additionally, temperature and humidity sensors continuously monitored ambient conditions.

Fig. 1. Experimental setup.

Following mixing, the fresh concrete is poured into molds, leveled, and covered with plastic film to minimize evaporation. After 3 hours, the side molds are removed, and displacement gauges are installed to obtain the initial reading. The samples are then placed in an open environment, and measurements are taken every 30 minutes during the first 2 hours and every 60 minutes thereafter for the next 9 hours. Water loss was determined from mass reduction relative to the initial water content. Regarding the drying shrinkage test, samples of the same size with embedded steel pins are covered for 24 hours. In turn, they are demolded for the measurement of shrinkage deformation.

III. RESULTS AND DISCUSSION

A. Water Loss and Plastic Shrinkage

The experimental results of the water loss process for the concrete mix and hardened concrete are presented in Table VII. The changes in temperature and humidity during the water loss and plastic shrinkage processes of the concrete mix and hardened concrete are presented in Figure 2Fig. 2. . Following the first 2 hours, concrete mixtures experienced a rapid loss of water ranging between 14% to 17% of the initial mixing water. By hour 4, the loss reached a percentage between 26% and 28%, while by hour 8, the cumulative moisture loss ranged from 34% to 37%. The shrinkage process of concrete over time is depicted in Figure 3.

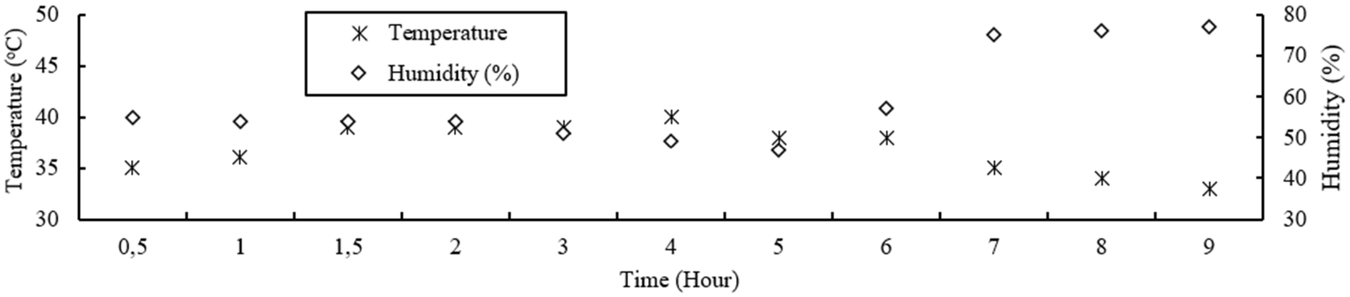

Fig. 2. Temperature and humidity timeseries.

TABLE VII. EXPERIMENTAL RESULTS OF WATER LOSS FOR CONCRETE MIX

Mixture	GGBFS/W	Distribution Coefficient (K_d)	C/W	Water Loss (%)											
				0 h	0.5 h	1 h	1.5 h	2 h	3 h	4 h	5 h	6 h	7 h	8 h	9 h
CP1	0%	1.57	2.21	0	6	12	15	17	25	28	31	33	35	37	40
CP2	35%	1.57	2.21	0	4	9	12	14	21	26	27	30	32	34	36
CP3	-	1.59	2.21	0	5	10	13	16	23	27	29	31	33	35	37

Regarding plastic shrinkage, concrete mixtures show rapid development within the first 4 hours. The shrinkage ranges from -1.404 to -1.530 mm/m. After hour 9, the shrinkage values are -1.702, -1.550, and -1.604 mm/m, respectively. The mixture of LS, CS, and GGBFS exhibited the lowest shrinkage due to denser aggregate packing and reduced water demand from GGBFS addition. In addition, GGBFS improved particle packing, enhanced water retention, minimized early moisture loss, and effectively mitigated plastic shrinkage. Consequently, this behavior demonstrates the role of GGBFS in enhancing dimensional stability and pavement durability.

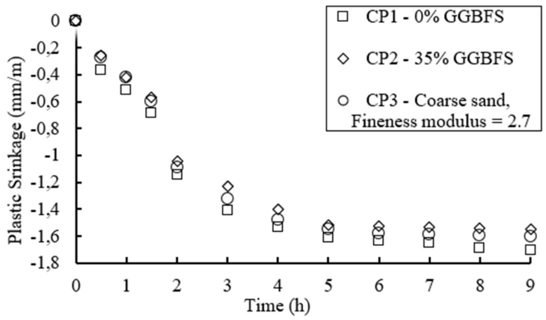

Fig. 3. Plastic shrinkage measurements timeseries.

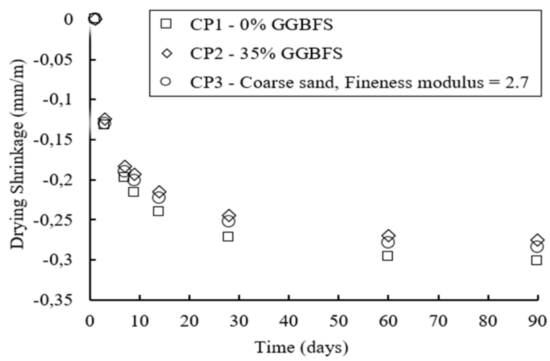

Fig. 4. Drying shrinkage of concrete timeseries.

B. Shrinkage of Concrete

The shrinkage test procedure was modified to satisfy the experimental conditions. The results, as presented in Figure 4, reveal that concrete under different mixtures exhibited shrinkage during the first 28 days, which gradually decreased over time. After 90 days, the shrinkage values were -0.301 mm/m, -0.275 mm/m, and -0.284 mm/m, respectively. The mixture containing 35% GGBFS presented the lowest shrinkage. To better simulate field conditions, certain samples were kept under laboratory air exposure without the 28-day moist curing specified in [20]. The observed shrinkage values were considered more suitable for pavement concrete. Overall, the LS, CS, and GGBFS mixture effectively limited drying shrinkage and improved dimensional stability.

This reduction in water loss and shrinkage observed in the LS, CS, and GGBFS mixture aligns with previous studies. Specifically, in [14], LS and superabsorbent polymers improved internal humidity and reduced autogenous shrinkage. Saturated recycled FAs decreased shrinkage by up to 90% [15]. In this study, shrinkage reduction was smaller (10-12%), but water loss remained more stable.

C. Mechanical Performance Considerations

Table VIII presents the 28-day compressive and flexural strength of the under-study mixtures. The results show that the CP3 mixture achieved the highest compressive strength values at 35.7 MPa and 4.5 MPa in flexural strength, exceeding the control mix (CP1) by approximately 5%. In contrast, the mixture with LS and CS (CP2) exhibited lower strength due to the increased porosity and weaker interfacial bonding of the lightweight particles. These findings indicate that the addition of GGBFS contributes to improved later-age strength through secondary hydration and pore refinement.

TABLE VIII. COMPRESSIVE AND FLEXURAL STRENGTH OF CONCRETE MIXTURES AT 28 DAYS

Mixture	Compressive strength (MPa)	Flexural strength (MPa)
CP1	33.9	4.2
CP2	32.6	4.1
CP3	35.7	4.5

IV. CONCLUSIONS

This study investigates the use of Ground Granulated Blast Furnace Slag (GGBFS) and Lightweight (LS) and Coarse Sand CS to mitigate water loss and shrinkage in concrete mixtures, and particularly in cement concrete pavement projects. Previous studies focused on dry climate conditions and lacked an in-depth analysis of the effects of these materials in hot and humid environments.

The experimental results show that concrete mixed with GGBFS exhibits lower shrinkage values, decreasing from -1.702 mm/m to -1.550 mm/m after 9 hours, compared to concrete using CS. Notably, the water loss of concrete with GGBFS reached 37% after 8 hours. These findings highlight the role of GGBFS in minimizing shrinkage and maintaining moisture, a factor not previously analyzed in detail under hot and humid climatic conditions.

The novelty of this paper lies in the combination of GGBFS with LS and CS as a solution not fully explored in previous studies. This combination improves the durability and stability of concrete in transportation infrastructure projects. The research results provide a solid scientific basis for applying internally cured concrete in cement concrete pavement projects.

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