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EXPERIMENTAL EVALUATION OF SHRINKAGE PROPERTIES IN CONCRETE INCORPORATING COAL MINE WASTE ROCK

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Abstract. This research investigates the properties of concrete utilizing coal mine waste rock (CMWR) as a substitute for river sand. The workability of fresh concrete is assessed through slump tests, revealing a decrease in a slump as the percentage of CMWR replacement increases. The density of the concrete mixtures increased with curing time, and the compressive strength also exhibited an upward trend but with lower values compared to the control concrete when CMWR was used as a replacement. The reduction in compressive strength ranges from 11.4% to 47.6% for CMWR replacement levels of 25% to 100%. The study also examines the influence of climate conditions, including temperature and humidity. Shrinkage deformation tests indicate that CMWR concrete demonstrates higher plastic and dry shrinkage than river sand concrete. CMWR concrete exhibits significantly higher drying shrinkage, attributed to the enhanced water absorption capacity of CMWR particles. These findings provide valuable insights into the performance of concrete incorporating CMWR and propose potential strategies for mitigating its effects. The research outcomes contribute to the knowledge base in the field and offer practical implications for the operation of CMWR in concrete applications.

Keywords: mine waste rock, shrinkage deformation, fine aggregate, dry shrinkage, plastic shrinkage, compressive strength.

1. INTRODUCTION

Concrete is the most common procedure of construction material because of its versatility, durability, and economic feasibility. However, one of the critical challenges associated with concrete is the occurrence of shrinkage deformation, which can lead to cracking and reduced serviceability of structures [1], [2]. Shrinkage deformation occurs due to moisture loss from the concrete matrix during drying development, causing volume reduction and subsequent tensile stresses [3].

There are two main types of shrinkage in concrete: (1) the first type is plastic shrinkage, which typically occurs during the initial curing stage of concrete after casting or construction. The nature of plastic shrinkage during this stage is due to water evaporation from the surface of the concrete, causing the surface of the concrete to shrink and the appearance of cracks to emerge; (2) the second type is drying shrinkage, which usually occurs during subsequent maintenance and hardening stages. This phenomenon is attributed to the moisture in the concrete over time through evaporation, causing the concrete to shrink and form cracks [4].

In recent years, there has been growing interest in using waste materials as partial replacements for conventional aggregates in concrete production [5–7]. In addition to the studies on the mechanical properties of using waste materials and recycled materials for concrete production, research on shrinkage has also received considerable attention from researchers. Previous studies investigated drying shrinkage in concrete using recycled aggregates [8,9] and concrete containing marble waste [10,11]. This approach offers the potential for sustainable construction practices and addresses the issue of waste management. One such waste material that has attracted attention is coal mine waste rock, a byproduct of coal mining operations. Coal mine waste rock is typically characterized by its high content of minerals and varying particle sizes, making it suitable for use as aggregate replacement in concrete. In Vietnam, on average per year, the volume of waste dumped on coal mining sites was about 150 million m^3; existing waste dump reserves were over 1.3 billion m^3. Incorporating coal mine waste rock into concrete offers the potential to mitigate the environmental impact associated with waste disposal while concurrently enabling the exploration of enhanced concrete properties and performance.

Based on the statistical analysis of the available literature, there was a lack of extensive research that contributed to investigating the shrinkage of concrete containing CMWR. Thus, the primary objective of this study is to evaluate the shrinkage deformation behavior of concrete when coal mine waste rock can use as an aggregate replacement. To assess the shrinkage properties of concrete, one can measure plastic shrinkage, drying shrinkage, and total shrinkage.

This investigation aims to provide insights into the feasibility of utilizing coal mine waste rock in concrete and address potential concerns related to shrinkage-induced cracking in concrete structures. The findings of this study contributed to the existing knowledge on the shrinkage deformation behavior of concrete using coal mine waste rock as aggregate replacement. Furthermore, the study wants to promote sustainable waste management practices by exploring the potential utilization of coal mine waste rock, thus reducing its environmental impact and conserving natural resources.

2. EXPERIMENTAL INVESTIGATION

2.1. Materials and mixtures

In this study, the concrete specimens were prepared using ordinary Portland cement (OPC), coarse aggregate in the form of limestone rock (LS), fine aggregate obtained from crushed sand made from coal mine waste rock (CMWR), and river sand (RS). Figure 1 shows the image of the fine aggregate, while Figure 2 depicts the particle size distribution curve for both the fine and coarse aggregates. The specific type of OPC used was OPC30, which was procured from Nghi Son Cement Company in Vietnam. This particular OPC variant was selected as it met the requirements for grade I cement as per the standards outlined in ASTM C1157 [12]. Table 1, and Table 2 present the chemical composition and physical properties of OPC30.

Table 1. Chemical composition of materials used in the study.

Component	Cement	CMWR	RS	LS
SiO_2	22.41	77.12	67.47	10.19
Fe_2O_3	2.87	4.47	5.61	0.87
Al_2O_3	3.98	9.4	14.04	3.02
TiO_2	-	0.26	0.54	-
K_2O	0.84	1.67	1.24	1.44
Na_2O	0.42	0.16	3.69	0.06
CaO	58.97	0.84	3.24	46.57
MgO	1.02	0.8	2.36	3.7
SO_3	2.18	0.32	-	-
LOI*	2.3	4.42	1.56	33.92
Free CaO	2.86	-	-	-
Specific surface, m^2/g	0.382	-	-	-

*LOI = Loss on ignition.

Table 2. Mechanical and physical properties of component materials.

Property	Unit	OPC	RS	CMWR	LS
Specific gravity	g/cm^3	3.08	2.64	2.61	2.57
Bulk density	kg/m^3	-	1451	1562	1410
Absorption	%	-	0.75	1.63	1.9
Los Angeles	%	-	-	-	21.4
Micro Deval	%	-	7.4	12.8	8.2
Fineness modulus		-	2.18	3.31	-
Setting time	Min	105 ÷ 210	-	-	-
Compressive strength at 28 days	MPa	35.3	-	-	-

Five mixtures were investigated: a control concrete (0CMWR -100RS) and four mixtures with varying proportions of CMWR and river sand (RS) replacements, namely 25% (25 CMWR-75RS), 50% (50CMWR-50RS), 75% (75CMWR-25RS), and 100% (100CMWR-0RS). LS was used as the coarse aggregate for all samples. Table 3 summarizes the mixture ratios and materials used to achieve a C20/25-grade concrete.

Table 3. The proportions of the material constituent with replacement CMWR.

Mixture	Ratio, %	Cement, kg	LS, kg	RS, kg	CMWR, kg	Water, dm^3
Mix 1	0	376	1020	738	0	185
Mix 2	25	376	1020	553.5	184.5	185
Mix 3	50	376	1020	369	369	185
Mix 4	75	376	1020	184.5	553.5	185
Mix 5	100	376	1020	0	738	185

Figure 1. CMWR and river sand were used in the experiment.

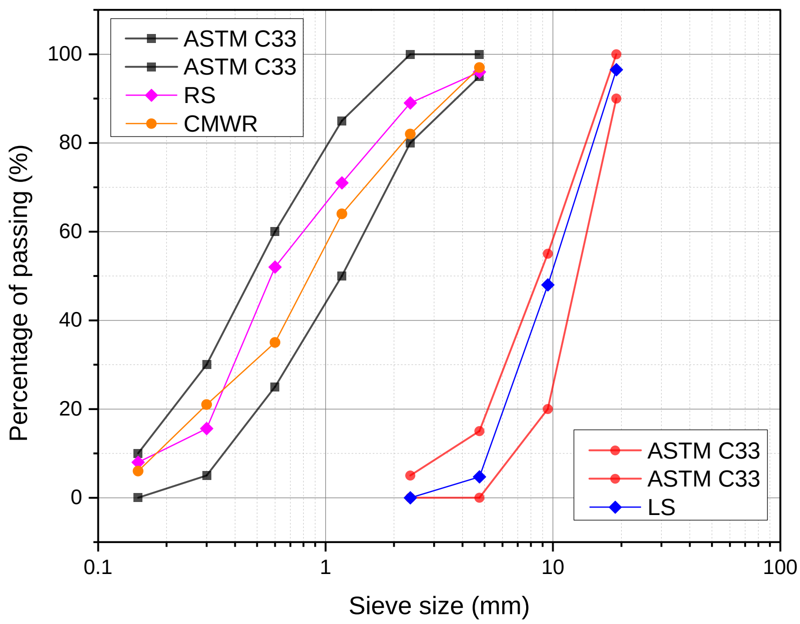

Figure 2. The particle size distribution curve of the aggregates.

2.2. Experimental procedures

For the Dmax of the aggregate was less than 25 mm, the Abraham cone (truncated cone) has a bottom diameter of 200 mm, top diameter of 100 mm, and height of 300 mm used to determine the slump of fresh concrete mix according to ASTM C143 [13]. The unit of a slump is centimeters (cm) and defined as the difference between the height of the Abraham cone and the height of the highest point of the concrete mix after removing the Abraham cone (Fig. 3).

The density of concrete is determined according to ASTM C642 [14]. First, fill the cylindrical measure with freshly mixed concrete in three even layers, compacting each layer by rod 25 times with a tamping rod. After each layer, remove any excess concrete using a straightedge. Next, weigh the filled cylindrical measure with the concrete and make a note of this weight. Following that, empty the measure of concrete and ensure it is thoroughly cleaned. Fill the measure with water and determine its weight, recording this measurement. Then, transfer the water from the measure into a separate container and add the freshly mixed concrete. Finally, weigh the filled measure with the concrete, record this weight, and compute the concrete's density (unit weight) using the formula:

Density = (Weight of Concrete - Weight of Measure) / Volume of Measure

Cylindrical concrete specimens with dimensions of 150x300 mm were subjected to water curing at a controlled temperature of 25±2°C. The curing process of concrete samples adheres to the guidelines specified in ASTM C192 [15]. To evaluate the compressive strength, cylindrical specimens with a diameter of 150 mm and a height of 300 mm underwent a test following ASTM C39 [16]. The test employed a universal testing machine (UTM) for accurate measurements and analysis (Fig. 3).

The concrete shrinkage is conducted according to ASTM C157 [17] (Fig. 3). First, introduce the specimens to a humid environment maintained. Subsequently, measure the initial length of the specimens, documenting these values meticulously, using calipers or a length comparator. Next, extract the specimens from the moist room, gently remove any excess surface water, and conduct precise weight measurements. Transition to the drying phase by placing the specimens in an oven set at a constant temperature of 100±5°C. Continuously monitor the drying process until there is no substantial change in weight. After the drying process concludes, measure the specimens' final length with precision. Utilize the following formula to calculate the dry shrinkage of the concrete, whether expressed in millimeters:

Dry Shrinkage (millimeters) = Initial Length - Final Length

Figure 3. Experiments were performed in the study.

3. RESULTS AND DISCUSSION

3.1. Workability of fresh concrete

The workability of a concrete mixture refers to its ability to adapt and perform during the construction process and after setting. In other words, workability is one of the essential properties of fresh concrete and determines its quality. The workability of a concrete mixture can determine through slump tests. The results of the slump tests are in Fig. 4.

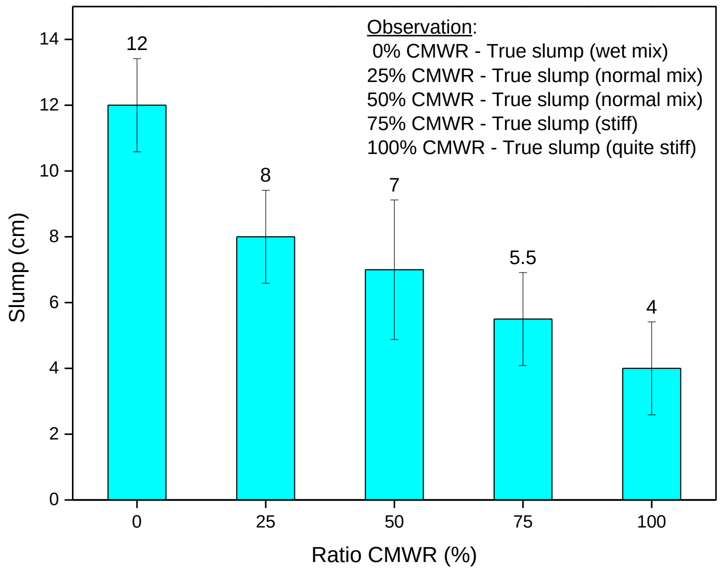

Figure 4. The slump of the mixture at different ratios CMWR.

The slump of concrete decreased as the percentage replacement of CMWR increased; The highest achieved was 12 cm for the reference concrete, and the lowest was 4 cm for concrete with 100% CMWR. Thus, the target slump, accepted range of 5-12 cm. Based on the experimental results, the workability of concrete was deemed reasonable and reliable with CMWR replacement content from 0% to 50%. Concrete replacing 100% RS by CMWR exhibited a slump of 4 cm, and visual observation indicated a highly stiff mixture. Concrete with 75% replacement of CMWR had a slump of 5.5 cm, which was close to the allowable slump target range, but visually eyes the mix appeared relatively stiff. The decreased workability in concrete with an increasing CMWR replacement rate can attribute to multiple factors. Firstly, the angular shape of CMWR particles facilitates their interlocking between aggregate particles, resulting in reduced porosity of the mixture [18]. Secondly, the presence of CMWR particles with a size range of 0.075-0.14 mm, which was more abundant compared to river sand [19], can contribute to the decrease in a slump. Lastly, CMWR exhibits a higher water absorption capacity than river sand [6], which further impacts the workability of the concrete mixture. As for coal mine waste rock absorbing more water than the river sand, we proposed the purpose of either washing or soaking the CMWR before mixing or increasing the concrete mix water content when using CMWR, surpassing the water content required when using river sand.

3.2. Density and compressive strength

Figure 5 illustrates the density of concrete containing river sand for CMWR. It observed that the bulk density of concrete mixtures for all blend proportions (i.e., substitutions of 0%, 25%, 50%, 75%, and 100% CMWR) increased as the curing time advanced. On the 28th day, the concrete achieved the highest density, and there was a trend of increasing density as the percentage of CMWR substitution increased.

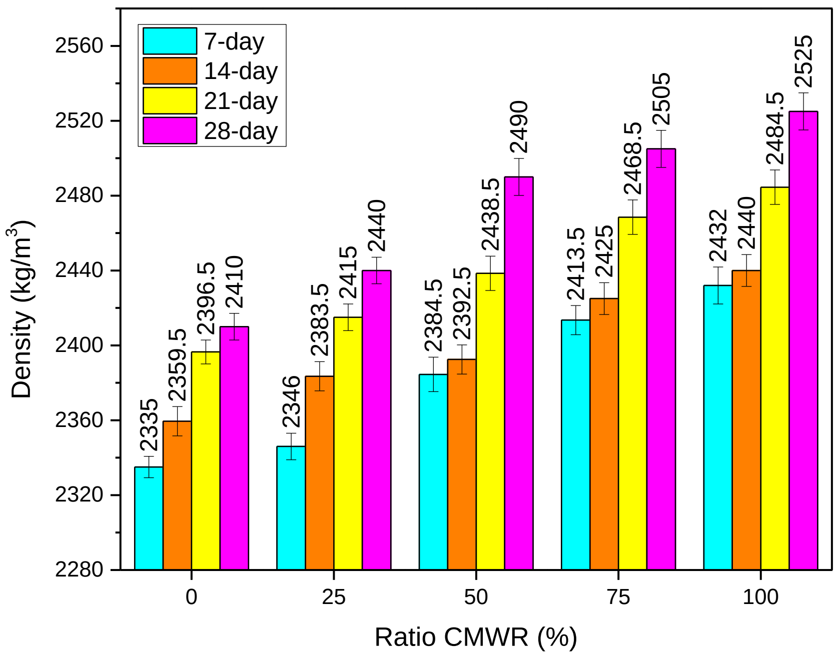

Figure 5. The density of mixtures at different ratios of CMWR.

The compressive strength of all blend proportions increased as the curing time advanced. The compressive strength values decreased as the percentage of CMWR substitution increased (Fig. 6). The substitution of 100% CMWR resulted in the lowest compressive strength value of 11.9 MPa on the 28th day. The compressive strength of all concrete mixtures made with CMWR was lower than the compressive strength of the control concrete. However, the compressive strength of the 25% CMWR concrete, at 20.1 MPa, was close to the compressive strength of the control concrete, which was 22.7 MPa. The reduction in compressive strength at 28 days for CMWR-concrete compared to river sand concrete was 11.4%, 21.6%, 32.6%, and 47.6% for the substitution of 25%, 50%, 75%, and 100% CMWR, respectively. The percentage reduction varied depending on the percentage of river sand substitution with CMWR, but it was not directly proportional.

The reasons behind this variation with the following factors: (1) The replacement of a significant amount of river sand with CMWR led to excessive fine particles. Despite the constant water-to-cement ratio (W/C), the reduction in water content required for cement hydration resulted in a decrease in compressive strength [19,20]; (2) Maybe, the occurrence of a small amount of coal within the grains of CMWR can lead to cracks when subjected to compressive forces. These cracks tend to form and reconnect rapidly, resulting in a reduction in the compressive strength of the concrete.

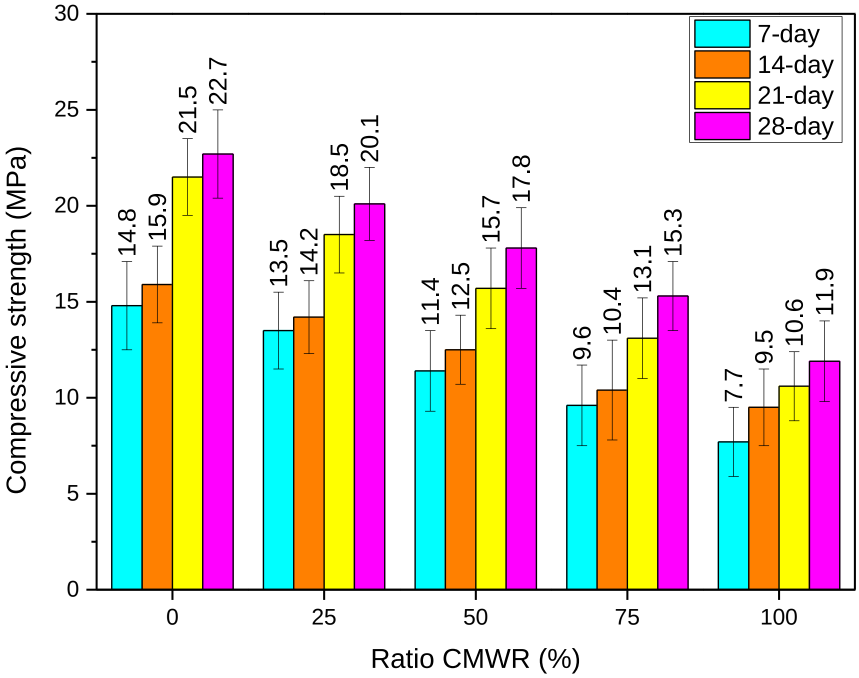

Figure 6. Compressive strength of mixtures at different ratios of CMWR.

3.3. Effect of climate

The climate data captured during the experiment encompassed temperature and humidity parameters, serving as representative indicators. The average daily temperature during the four months of conducting the experiments fluctuated between 25ºC and 35ºC, while the average daily humidity ranged from 55% to 95%. Figure 7 illustrates the median daily temperature and humidity over the four months.

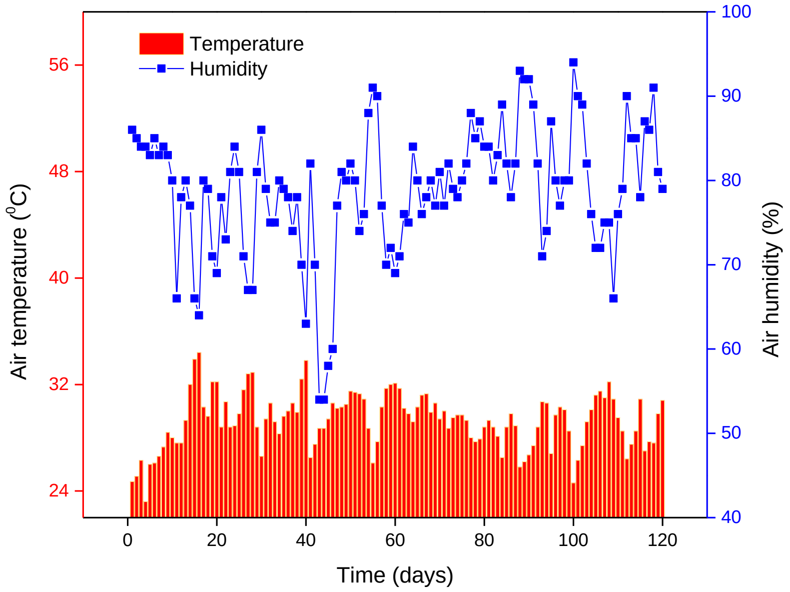

Figure 7. Temperature and humidity during the experimental period.

3.4. Shrinkage deformation

3.4.1. Plastic shrinkage deformation

The shrinkage development occurs immediately after the concrete mixture is shaped, still in a plastic state, and undergoing structural formation, without bearing any load. If the amount of water lost per unit area exceeds the amount of water transported to the surface through absorption and if this loss is significant, it can lead to surface cracking. In other words, plastic shrinkage occurs when the hydration process in concrete depletes the moisture content within the concrete. Therefore, plastic shrinkage is the shrinkage deformation of concrete that has protected from environmental moisture factors, which are among the factors that can influence shrinkage deformation in concrete. It typically happens within the first few hours after the concrete has been placed and while it is still in its plastic, moldable state. Hence, plastic shrinkage in concrete is a deformation phenomenon influenced by environmental humidity. This factor is considered one of the contributors to shrinkage deformation in concrete. The results of the concrete's plastic shrinkage test are shown in Figure 8.

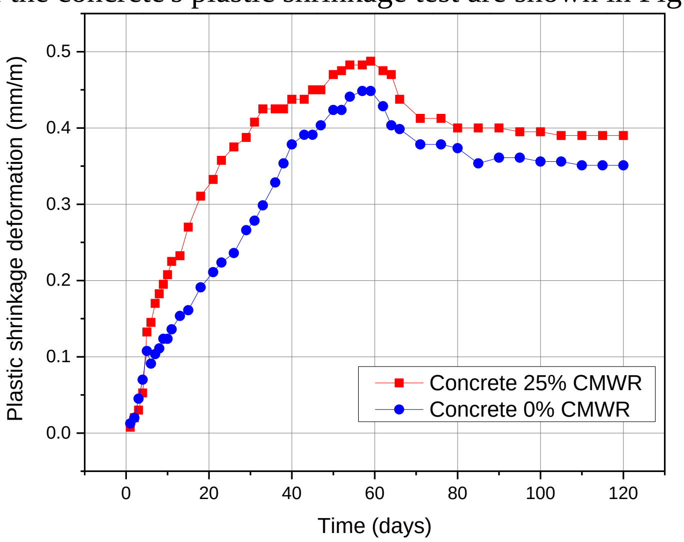

Figure 8. Plastic shrinkage deformation.

The plastic shrinkage of CMWR concrete was higher than concrete containing river sand. It can attribute to the higher specific surface area of the CMWR aggregates because of crushing the waste rock. Additionally, these aggregates contributed cementitious particles that did not absorb water due to certain minerals current in the waste rock. It allowed for an extended hydration process over a longer period [21].

In the initial stage, river sand and CMWR fine aggregates exhibited similar plastic shrinkage development rates. The plastic shrinkage of concrete using river sand was lower compared to concrete using CMWR aggregates; curves had a relatively similar shape (Fig. 8). The plastic shrinkage curve of CMWR concrete typically continued to increase until reaching a maximum value of 0.4825 mm/m after 60 days. It then decreased until extending a steady of 0.39 mm/m at 120 days. The plastic shrinkage curve of concrete using river sand followed a similar pattern to the CMWR concrete curve. It also increased slowly during the first 40 days of the test, then continued to rise until day 60, followed by a gradual decrease during the last 20 days of the experiment. The maximum plastic shrinkage of regular concrete was 0.4625 mm/m after 59 days, while the maximum plastic shrinkage for 25% CMWR was 0.4485 mm/m after 58 days. The plastic shrinkage of concrete using CMWR (with 25% replacement) was generally about 1.1 times higher than the elastic shrinkage of concrete containing river sand.

3.4.2. Total shrinkage deformation

The total shrinkage deformation of concrete can influence by all factors that can cause shrinkage. These factors can classify into internal factors, such as moisture loss due to hydration, and external factors, such as temperature and humidity. Concrete prisms are left unprotected and exposed directly to real-time climate conditions for determining the total shrinkage. The total shrinkage of concrete using river sand and CMWR (with 25% CSM) is shown in Figure 9. The overall shrinkage of concrete containing CMWR was higher than that of concrete containing river sand; curves have a similar shape (Fig. 9).

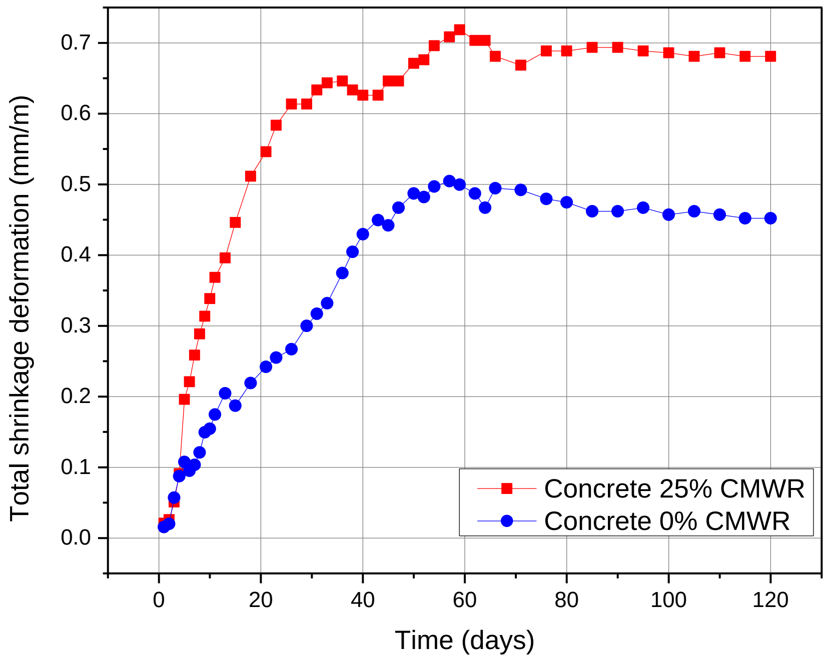

Figure 9. Total shrinkage deformation.

In the case of concrete incorporating river sand, the total shrinkage curve displayed a rapid initial increase. It continued to increase until it reached a final total shrinkage value of only 0.5 mm/m after 52 days before starting to decrease. In the case of concrete containing CMWR as aggregate, the curve of total shrinkage exhibited a rapid initial increase and continued rise until it reached a peak value of 0.7 mm/m after 80 days. Subsequently, it showed a slight decrease. Therefore, the total shrinkage of CMWR (with 25% replacement) was approximately 1.7 times higher than that of concrete containing river sand.

3.4.3. Dry shrinkage deformation

Drying shrinkage refers to the change in length experienced by a mature concrete cylinder after being immersed in water and subsequently dried under specific conditions. Drying shrinkage, akin to the hydration process of cement, is a permanent phenomenon that concrete experiences when exposed to dry environments. It occurs over an extended period, typically weeks or months after the concrete has been placed and has reached its hardened state.

The drying shrinkage curves of concrete containing CMWR and river sand are shown in Figure 10. The maximum drying shrinkage of concrete using river sand was 0.122 mm/m, while for CMWR, it was 0.297 mm/m. In other words, the drying shrinkage of concrete containing CMWR (with 25% replacement) was 2.43 times higher than that of concrete containing river sand.

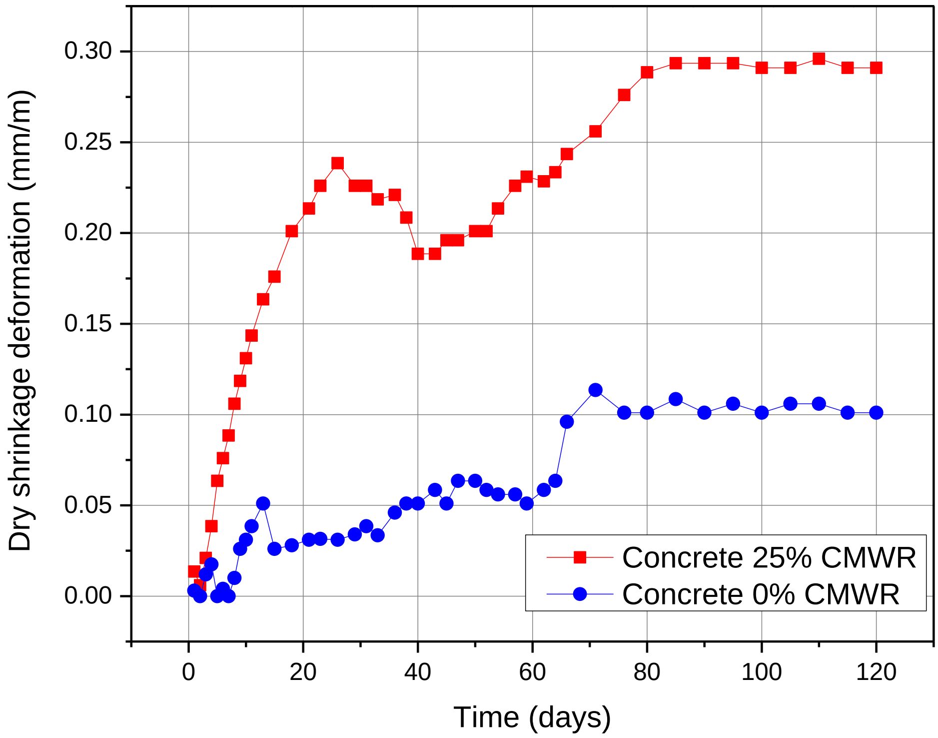

Figure 10. Dry shrinkage deformation of concrete.

The drying shrinkage of concrete using CMWR was significantly higher than that of concrete using river sand, and the curves did not follow a conventional pattern and were not similar. It could attribute to the CMWR particles having a higher water absorption capacity than the river sand, which affected the rate of increase in drying shrinkage.

4. CONCLUSION

Based on the obtained results, the following conclusions were drawn:

- The water absorption capacity of CMWR aggregates from coal mine waste rock was higher compared to river sand aggregates. Therefore, the workability of concrete containing CMWR decreased as the CMWR content increased. When using aggregates sourced from mine waste rock, it was crucial to closely monitor the water content in the concrete mixture, as the water absorption capacity of CMWR aggregates would consistently vary. Therefore, careful consideration was necessary when utilizing CMWR in ready-mixed concrete under dry and hot environments.

- The density of concrete containing CMWR was higher than that of concrete containing river sand at any age. The percentage increase in density for replacing 25%, 50%, 75%, and 100% of river sand with CMWR was 1.2%, 3.3%, 3.9%, and 4.8%, respectively.

- The compressive strength of concrete containing CMWR decreases as the CMWR content increases. However, the compressive strength of concrete containing 25% CMWR is closer to that of the control concrete than the replacement percentages of 50%, 75%, and 100% CMWR.

- The temperature and humidity have demonstrated their influence on the drying shrinkage deformation of concrete, as the overall drying shrinkage deformation of concrete, irrespective of the CMWR content, consistently exceeds the plastic shrinkage deformation.

- Both the concrete containing CMWR and the concrete containing river sand exhibited similar rates of drying shrinkage development, particularly at early ages. The total drying shrinkage deformation of the concrete containing CMWR (with 25% replacement) was 1.3 times higher than that of the concrete containing river sand. The plastic shrinkage deformation of the concrete containing CMWR was 1.1 times higher than that of the concrete containing river sand (with 25% replacement). The dry shrinkage of the concrete containing CMWR (with 25% replacement) was 2.9 times higher than that of the concrete containing river sand.

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