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Impact of Curing Temperature on the Compressive Strength of Cement Mortars Incorporating Electric Arc Furnace Slag

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ABSTRACT

To reduce the environmental impact of the cement industry and lower production costs, researchers have explored using by-product materials, such as fly ash, silica fume, and slag, as partial replacements for Portland cement in concrete production. This experimental study investigates how curing temperatures (20, 40, and 60°C) affect compressive strength of cement mortars that incorporate electric arc furnace slag (EAFS) at varying levels (0, 10, 20, and 30% by weight). The compressive strength of mortar specimens was evaluated at 3, 7, 28, 56, and 90 days. Additionally, ultrasonic pulse velocity tests were conducted on the mortar specimens. The results showed that the performance of electric arc furnace slag is quite sensitive to temperature changes. Overall, the compressive strength of the mortars improved over time, and both the amount of slag used and the curing temperature played significant roles in the rate of strength development.

Keywords: Electric Arc Furnace Slag, Replacement level, Curing Temperature, Compressive Strength

تأثير درجة حرارة المعالجة على قوة الضغط للمونة الأسمنتية المحتوية على خبث فرن القوس الكهربائي

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ملخـــــــص البحـــــــث

لتقليل الأثر البيئي لصناعة الأسمنت وخفض تكاليف الإنتاج، استكشف الباحثون استخدام مواد ثانوية مثل الرماد المتطاير وغبار السيليكا والخبث كبدائل جزئية للأسمنت البورتلاندي في إنتاج الخرسانة. تبحث هذه الدراسة التجريبية في كيفية تأثير درجات حرارة المعالجة (20 و40 و60 درجة مئوية) على مقاومة الضغط للمونة الاسمنتية المحتوية على خبث فرن القوس الكهربائي (EAFS) بنسب متفاوتة (0 و10 و20 و30% وزنًا). قُيِّمت قوة ضغط عينات المونة عند أعمار 3 و7 و28 و56 و90 يومًا. بالإضافة إلى ذلك، أُجريت اختبارات سرعة الموجات فوق الصوتية على عينات المونة. أظهرت النتائج أن أداء خبث أفران القوس الكهربائي حساسٌ جدًا لتغيرات درجة الحرارة. وبشكل عام، تحسنت مقاومة ضغط المونة الاسمنتية بمرور الوقت، ولعبت كمية الخبث المستخدمة ودرجة حرارة المعالجة دورًا هامًا في سرعة تطور المقاومة.

الكلمات الدالة: خبث فرن القوس الكهربائي، مستوى الاستبدال، درجة حرارة المعالجة، مقاومة الضغط.

1. Introduction

The significance of cement replacement materials and supplementary cementitious materials (SCMs) is steadily growing within the cement industry, particularly in relation to economic, technological, and environmental considerations. Many studies [1-6] have explored the potential of utilizing by-products like fly ash, silica fume, and slag as partial substitutes for Portland cement (PC) in concrete production. Slag can be categorized into three main types based on how it's produced: blast furnace slag (BFS), basic oxygen furnace slag (BOFS), and electric arc furnace slag (EAFS). BFS is a by-product of iron production, while BOFS and EAFS are generated during steel production [7]. Air-cooled slag (BFS) can be used as an aggregate, but it is more commonly utilized as an SCM in the form of water-cooled slag, also known as ground granulated blast furnace slag (GGBFS). This type of slag has been shown to enhance the properties of concrete when used as a cement binder [8]. Currently, steel slag (EAFS) is primarily used in low-value applications, such as aggregates in asphalt concrete and fillers in foundation engineering [9, 10]. Electric Arc Furnace Slag (EAFS) is considered to have low reactivity when used as a Supplementary Cementitious Material (SCM), primarily due to its low CaO/SiO_2 ratio and the air-cooling process typically employed during its production [11]. Alsadig and Wagialla [12] investigated the impact of incorporating EAFS on the strength properties of mortars and concluded that EAFS, when used as a partial replacement for cement, exhibits good pozzolanic properties. Wang and Suraneni [13] noted that steel furnace slag (SFS) may have variable chemistry and mineralogy, which explains the variability in its hydraulic or pozzolanic reactivity. Their study found that compressive strength testing can classify steel slag materials as SCMs. Brand and Fanijo [8] emphasized that differences in steelmaking processes result in variations in the chemistry and mineralogy of SFS. The mineral composition of SFS is determined not only by the steelmaking method and the fluxing materials applied but also by how the slag is cooled. The cooling technique plays a major role in shaping the characteristics and makeup of SFS, affecting factors such as crystallinity level, particle size, the presence of free CaO and MgO, and its overall crystalline structure. Santamaria-Vicario et al. [14] reported that the compressive and flexural strengths of cement mortars increased as the slag content in the mix was raised, particularly at 90 days of testing. Similarly, a study by Pan et al. [15] found that replacing 10% of cement with steel slag led to a 6% improvement in compressive and splitting tensile strength after 28 days. Amin et al. [16] reported that the compressive strength of mortars containing Electric Arc Furnace Slag (EAFS) cured at 20°C was consistently lower than that of the control mortar. However, compressive strength improved with increasing fineness of EAFS, particularly at 20 and 30% cement replacement, with slag-fine producing a compressive strength comparable to the control mortar at curing temperatures of 40 and 60°C, respectively. This improvement was attributed to enhanced hydration reactions and the high pozzolanic reactivity of the finer EAFS (SF). Mortars without cement substitution demonstrated higher early-age compressive strength but lower later-age strength when exposed to elevated curing temperatures after casting. Similar trends were observed in mortars containing varying fineness and proportions of both EAFS and fly ash (FA), with higher curing temperatures resulting in increased early-age and reduced later-age compressive strength. A study by Abdalkader et al. [17] showed that the compressive strength of mortar specimens increases by about 2.5%, 7%, and 13% for periods of 28, 56, and 90 days, respectively, when 10% of the cement is replaced with 400 m^2/kg EAFS fineness. In this experimental study, the impact of curing temperature (20, 40, and 60°C) on the compressive strength of 50 mm mortar cubes made with local electric arc furnace steel slag was examined. Four different substitution levels of steel slag (0, 10, 20, and 30% by weight of cement) were used. Additionally, the ultrasonic pulse velocity through the mortar specimens was analysed.

2. Experimental Program

The subsequent subsections detail the materials used, mixture proportions, mixing protocols, specimen curing regimens, and testing procedures.

2.1 Materials Used

In this research, CEMI 42.5N cement sourced from the Al Fataiah Cement Factory (a local manufacturing plant) was used. This cement meets the standards specified in BS EN 197-1:2000. The physical and chemical properties of the cement are presented in Table 1. Electric arc furnace slag (EAFS) in aggregate form, Figure 1 was obtained from a steel factory in Benghazi, with an average particle size ranging from 2 to 5 cm. To achieve the required fineness (350 m^2/kg Blaine surface area), the slag was ground into a fine powder. The grinding process involved the use of two types of mills: ball mills and ring mills. The resulting slag powder Figure 2 was incorporated as a partial cement replacement in the mixtures at varying percentages of 10, 20, and 30%. The oxide composition of the slag was analysed using X-ray fluorescence (XRF) spectroscopy, as shown in Table 1. Standard silica sand, obtained from the Al Fataiah Cement Factory, was also employed in this study. This sand met the requirements specified in BS EN 196-1:2005. Additionally, tap water available in the civil engineering laboratory was used to prepare all mortars.

Table 1. Physical and chemical analysis of used cement and electric arc furnace slag (EAFS).

Item	CEMI	EAFS
Physical properties		
Specific gravity (g/cm^2)	3.13	3.19
Fineness (m^2/kg) (Blaine)	320	350
Chemical properties (Oxides, % by weight)		
SiO_2	20.86	35.8
Al_2O_3	5.6	13.5
CaO	62.39	25.2
Fe_2O_3	4	10.4
MgO	1	1.52
SO_3	2.93	-
K2O	-	0.38
L.O.I	2.52	-

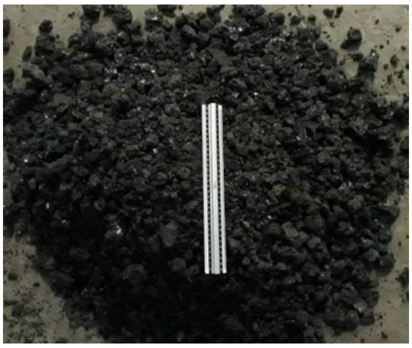

Figure 1. Slag in aggregate form.

Figure 2. EAFS after grinding.

2.2 Proportions and Mixing Procedure

In this study, the mortar mixes were designed by replacing cement with electrical arc furnace slag (EAFS), at various substitution ratios (0, 10, 20, and 30%). Detailed information on mixes is given in Table 2. The water-to-cementitious materials and the sand-to-binder ratios in all mixes were kept at 0.485 and 2.75, respectively. The mortars were mechanically mixed using a Hobart mixer according to the standard method as specified by ASTM C305.

Table 2. Mix proportions for mortar specimens.

Mix	EAFS (%)	Curing Temp. (°C)	Per weight of binder			
			CEM I	EAFS	Sand	Water
CM (Control)	0	20	1	0	2.75	0.485
PC.40	0	40	1	0	2.75	0.485
PC.60	0	60	1	0	2.75	0.485
10%EAFS.20	10	20	0.9	0.1	2.75	0.485
10%EAFS.40	20	40	0.8	0.2	2.75	0.485
10%EAFS.60	30	60	0.7	0.3	2.75	0.485
20%EAFS.20	10	20	0.9	0.1	2.75	0.485
20%EAFS.40	20	40	0.8	0.2	2.75	0.485
20%EAFS.40	30	60	0.7	0.3	2.75	0.485
30%EAFS.20	10	20	0.9	0.1	2.75	0.485
30%EAFS.40	20	40	0.8	0.2	2.75	0.485
30%EAFS.60	30	60	0.7	0.3	2.75	0.485

2.3 Curing of specimens

After casting, the mortar specimens were covered with thin polythene sheets and left to cure under laboratory conditions for a period of 24 hours. Thereafter, the specimens were demoulded and stored in curing water at 20, 40 and 60°C until test ages (3, 7, 28, 56, and 90 days). Curing tanks controlled at 40 °C and 60°C are shown in Figure 3.

Figure 3. Curing water tanks at 40, and 60°C.

2.4 Testing procedure

Compressive strength tests on 50 mm mortar cubes were conducted in accordance with ASTM C 109. The ultrasonic pulse velocity test was also performed on mortar specimens according to ASTM C597.

3. Results and Discussion

The following subsections present the results and analysis regarding the thermal influence on the compressive strength and ultrasonic pulse velocity (UPV) of mortars.

3.1 Effects of Temperature on Compressive Strength

The impact of temperature on mortar compressive strength is examined in the following subsections.

3.1.1 Mortar Specimens without EAFS

Figure 4 illustrates how the compressive strength of control mortar specimens (without EAFS) changes over time under different curing temperatures (20, 40, and 60°C). The graph clearly shows that all curing conditions lead to an increase in compressive strength as time goes on, meaning the cement mortars continue to get stronger. At the 3-day mark, the mortar cured at ambient temperature (CM mix) has the lowest strength, around 20 MPa. Over time, it gradually gains strength, reaching about 45 MPa by 90 days, but the increase is slow and steady. In contrast, the mortar cured at 40°C exhibits much higher strength early on. After just 3 days, its strength hits approximately 24 MPa, indicating that higher temperatures accelerate hydration. Although the rate of strength gain slows after 28 days, it continues to grow, reaching around 51 MPa by 90 days. This shows that curing at 40°C boosts early strength development without sacrificing long-term durability. The specimens cured at 60°C achieve the highest initial strength, reaching about 32 MPa at 3 days, with rapid gains up to 7 days. However, as time progresses (at 28, 56, and 90 days), the rate of strength gain is slower compared to samples cured at 40°C. This suggests that while 60°C accelerates early strength, it may slightly hinder long-term strength due to potential issues like thermal cracking or less efficient hydration.

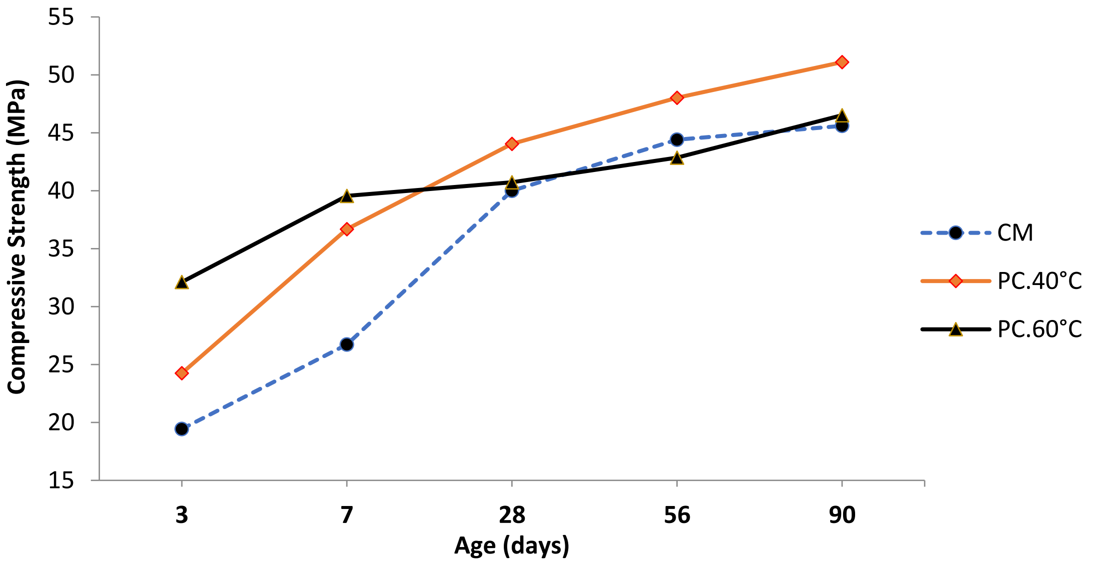

Figure 4. Compressive strength of 0% EAFS mortars at different curing temperature.

3.1.2 Mortar Specimens with 10% EAFS

Figure 5 shows how curing temperature (20, 40, and 60°C) affects the compressive strength of mortar specimens with 10% EAFS over time. The graph reveals that at higher temperatures of 40 and 60°C, the mortars gain strength more quickly compared to the lower temperature of 20°C. This is evident in the steeper curves for the 40 and 60°C specimens during the initial periods (3 and 7 days). The increased warmth speeds up the cement hydration process, resulting in quicker strength development early on. In contrast, at 20°C, the strength gain is slower, reflected in the lower compressive strength observed at both 3 and 7 days. By the 28 days, the specimens cured at 40 °C and 60°C nearly match or even slightly exceed the strength of those cured at 20°C. However, it's important to note that even though higher temperatures promote faster initial hydration, they may not create a dense microstructure in the long run.

At 90 days, the mortar specimens cured at 20°C ended up having the highest compressive strength, surpassing those cured at 40 and 60°C. The specimens at 40°C show moderate strength over time, while those at 60°C tend to have slightly lower long-term strength. This is likely due to the effects of prolonged high temperatures, which can lead to a less dense microstructure, micro-cracking, or reduced hydration over time, ultimately impacting compressive strength negatively.

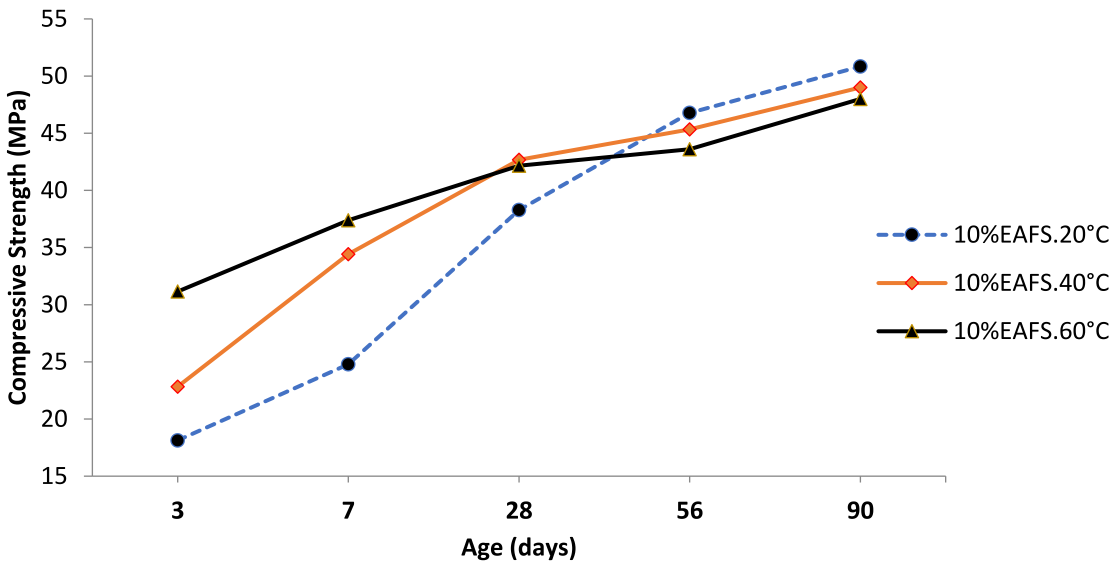

Figure 5. Compressive strength of 10% EAFS mortars at different curing temperatures.

3.1.3 Mortar Specimens with 20% EAFS

Figure 6 illustrates how curing temperature affects the compressive strength of mortar specimens containing 20% Electric Arc Furnace Slag (EAFS) over time. At 3 days, the compressive strength of the 20% EAFS mortar cured at 20°C is relatively low, about 15 MPa, suggesting that hydration and strength development are slower at room temperature. By 7 days, the strength increases to around 20 MPa, though this is still lower than what is achieved at higher temperatures. The graph clearly shows that higher curing temperatures speed up the hydration process for the 20% EAFS cement mortars. At 3 days, specimens cured at 40 and 60°C show higher compressive strengths of approximately 21 and 29 MPa, respectively. By 7 days, these strengths rise to about 32 and 35 MPa, significantly exceeding the strength at 20°C. At 28 days, the strength of the mortar cured at 20°C continues to improve, reaching around 35 MPa as hydration progresses steadily. In contrast, the strengths at 40°C and 60°C are approximately 40 and 37 MPa, respectively, indicating that elevated temperatures facilitate faster early strength gain. However, the rate of increase in strength starts to slow down compared to earlier stages. By 56 days and beyond, the compressive strength at 20°C gradually peaks around 45 MPa (by 90 days). At this point, the strength of the specimens cured at 40 and 60°C hovers around 42 and 39 MPa, respectively, indicating a plateau. By 90 days, the difference in strength between the 20 and 40°C curing temperatures becomes minimal, with both reaching about 45 MPa.

3.1.4 Mortar Specimens with 30% EAFS

Figure 7 shows how the curing temperature affects the compressive strength of mortar samples with 30% EAFS at various temperatures (20, 40, and 60°C). At 3 days, as the curing temperature rises, the compressive strength also increases, reaching its peak at 60°C with around 26 MPa. This suggests that higher temperatures speed up hydration. By 7 days, this pattern continues, with 60°C still producing the strongest samples, followed by 40°C and then 20°C. By 28 days, the strengths for all temperatures start

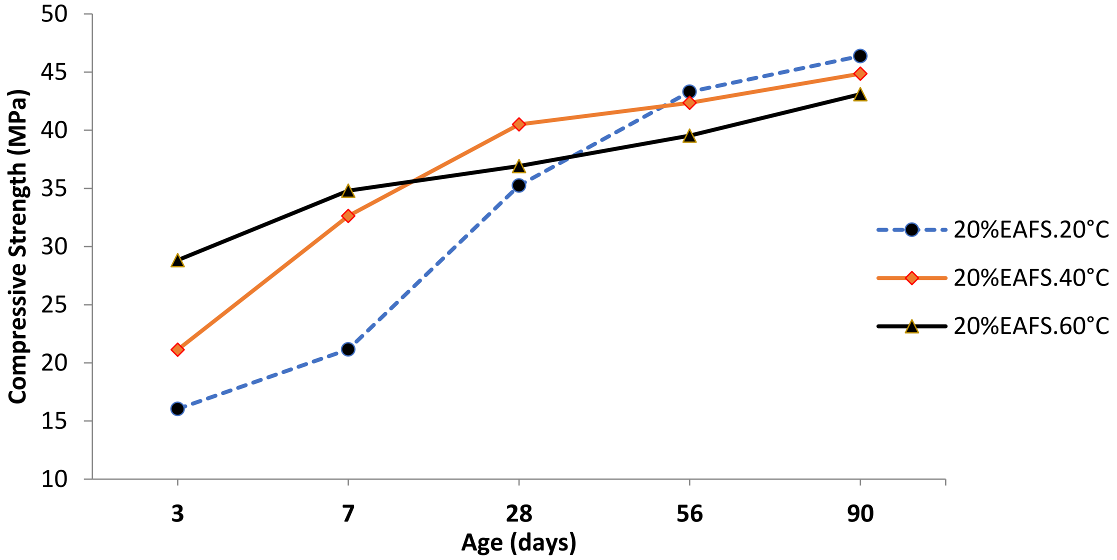

Figure 6. Compressive strength of 20% EAFS mortars at different curing temperature.

to even out, but interestingly, the samples cured at 40°C exceed those at 60°C, achieving greater strength. At 56 and 90 days, the samples cured at 20°C and 40°C show similar strength levels (around 38 MPa at 56 days and 40 MPa at 90 days), both outpacing the 60°C samples.
It seems that the 60°C curing temperature leads to lower compressive strength over time compared to the 40°C, likely due to long-term microstructural issues from rapid initial hydration. Bougara et al. [18] noted that the amount of bound water in slag concrete increases with higher curing temperatures, indicating that slag can be thermally activated. Their findings suggest that 40°C is optimal for both hydration and strength.

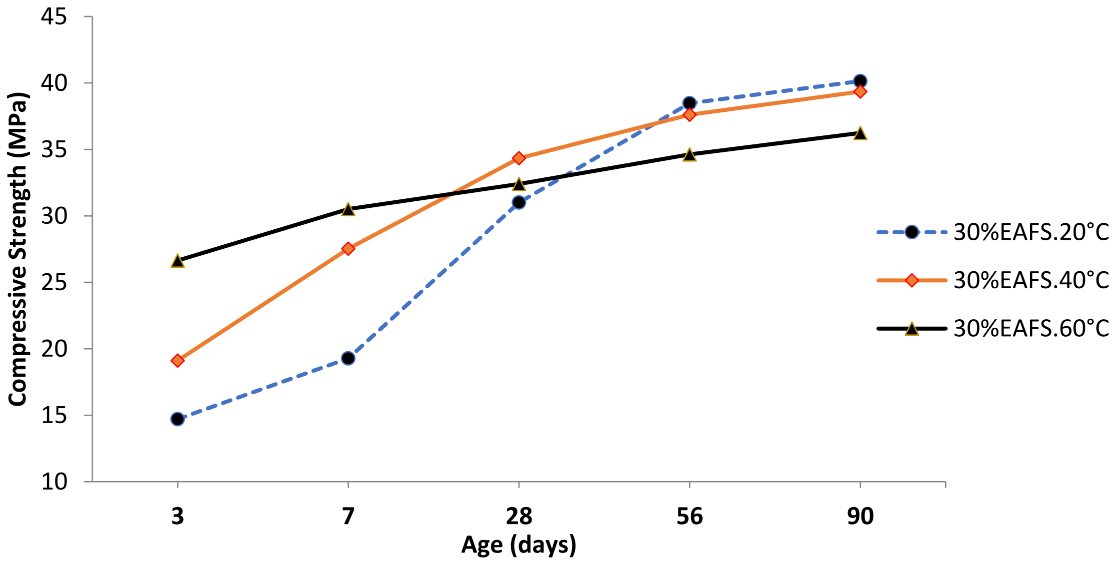

Figure 7. Compressive strength of 30% EAFS mortars at different curing temperature.

3.2 The Ultrasonic Pulse Velocity Results

Figures 8-11 show the influence of curing temperatures on the ultrasonic pulse velocity of mortar specimens.

3.2.1 Mortar Specimens without EAFS

The results clearly show that higher curing temperatures (40°C and 60°C), greatly improve early ultrasonic pulse velocity (UPV) values, as illustrated in Figure 8. By day 3, samples cured at 60°C have UPV values that are about 30 to 40% higher than those cured at room temperature (CM), highlighting the significant enhancement in hydration reactions due to the heat. Figure 8 also reveals that the rate of UPV growth varies based on curing conditions. Samples cured at the high temperature of 60°C show a rapid initial increase in UPV but then experience slower growth over time. In contrast, samples cured at a temperature of 40°C show a steadier and consistent increase. The ambient-cured (CM) samples, while growing steadily, do so at a slower rate throughout the testing period. Importantly, even after 90 days, the samples cured at higher temperatures continue to show better UPV values. This suggests that they achieve a more complete hydration process, resulting in a denser microstructure and improved particle packing, even though the growth rates start to converge at later ages.

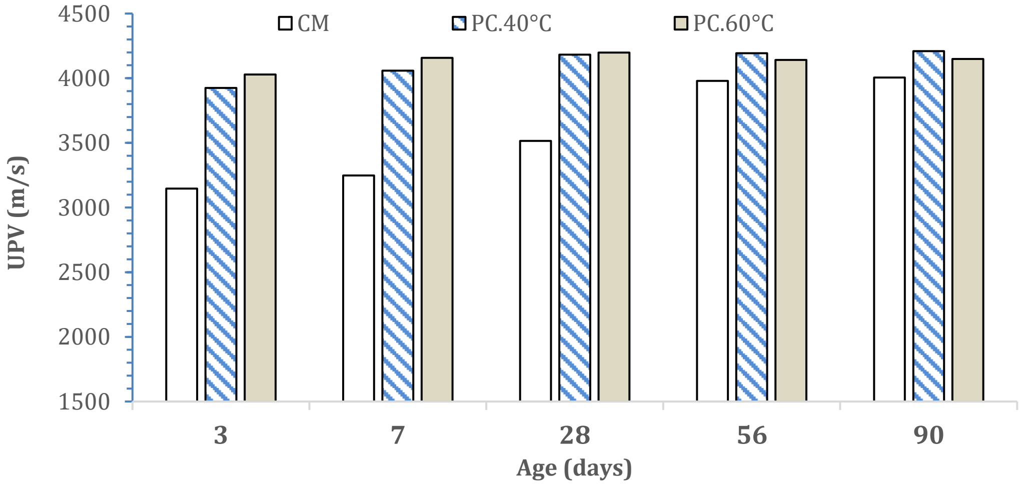

Figure 8. UPV for 0 % EAFS mortars at different curing temperature. `

3.2.2 Mortar Specimens with 10% EAFS

The samples cured at 40 and 60°C show significantly higher UPV values during the first 28 days, with improvements of about 15 to 25% compared to the samples at 20°C (see Figure 9). This increase is especially noticeable at 3 and 7 days, where the 60°C samples reach UPV values similar to those of the 28-day samples cured at 20°C. While the temperature differences lead to significant variations early on,

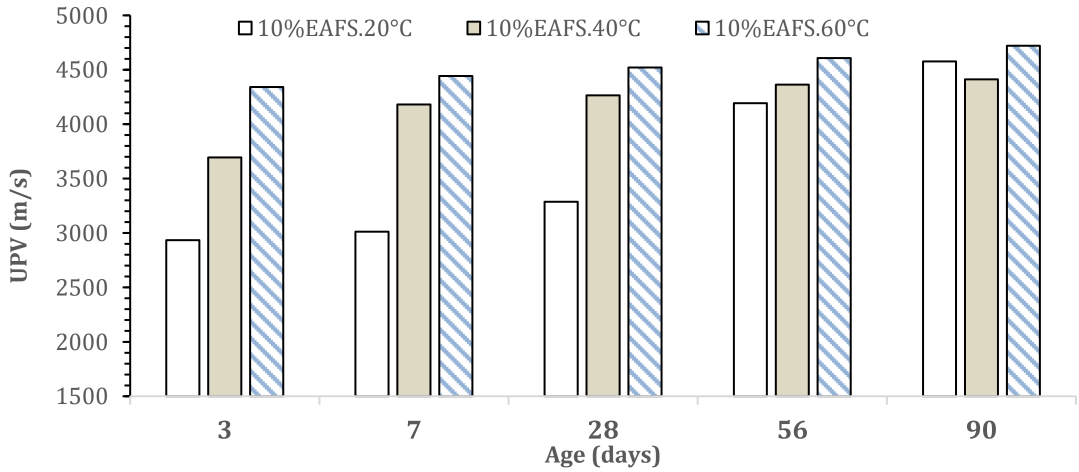

Figure 9. UPV for 10 % EAFS mortars at different curing temperature.

the advantage decreases considerably after 56 days. By 90 days, the 40 °C and 60°C samples only have a 5 to 8% edge over the 20°C samples, indicating that higher temperatures mainly accelerate the hydration process rather than improve the final results. Additionally, the smaller gains between 40 and 60°C, especially after 28 days, suggest that using excessive heat may not yield proportional benefits.

3.2.3 Mortar Specimens with 20% EAFS

Figure 10 illustrates that curing at high temperatures (40 and 60°C) generally results in higher Ultrasonic Pulse Velocity (UPV) values compared to standard curing at 20°C, especially during the initial stages (from 3 to 28 days). This indicates that high temperatures accelerate the development of early strength, likely due to increased pozzolanic reactions and quicker cement hydration. However, the fact that UPV values from different curing temperatures align more closely at later ages (56 and 90 days) suggests that while heat curing offers advantages early on, the long-term properties of the material may end up being similar.

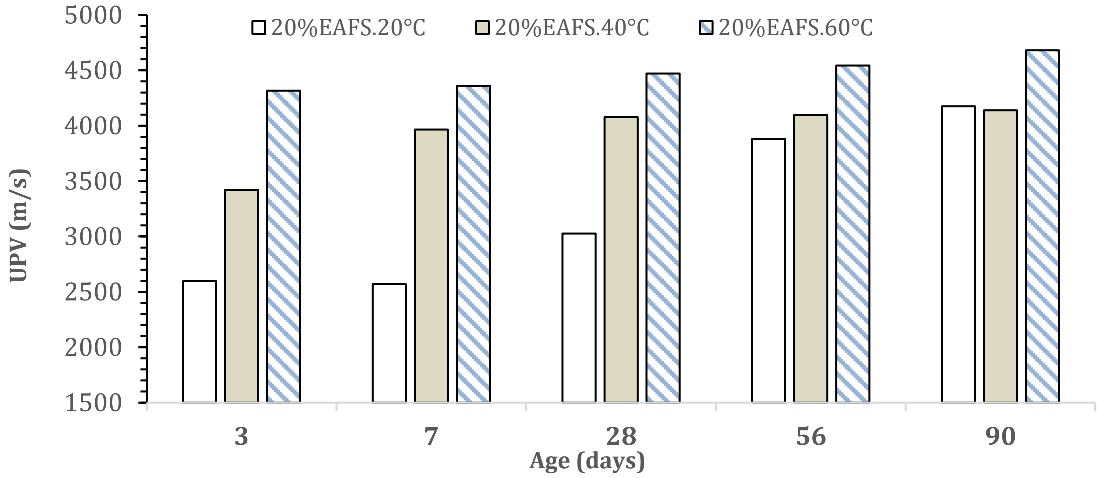

Figure 10. UPV for 20 % EAFS mortars at different curing temperature.

3.2.4 Mortar Specimens with 30% EAFS

Figure 11 shows how the ultrasonic pulse velocity (UPV) of 30% EAFS mortar samples changes over time at different curing temperatures. As the mortar matures, the UPV increases across all temperature settings, indicating that the material is gaining strength and becoming denser. Mortar cured at 40 and 60°C consistently exhibits higher UPV values than that cured at 20°C, suggesting that warmer conditions

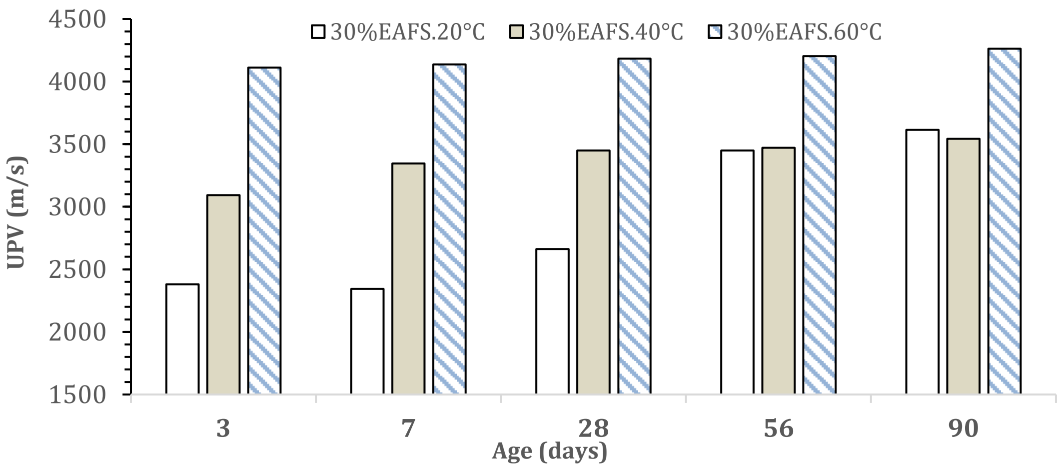

Figure 11. UPV for 30% EAFS mortars at different curing temperature.

accelerate hydration and enhance microstructure development. The most notable increases in UPV occur in the early stages (from 3 to 28 days), while differences between the temperatures become less significant later on (at 56 and 90 days), likely because hydration is nearly complete.

4. Conclusions

According to the test results, the experimental investigation reveals that the compressive strength of mortars incorporating electric arc furnace slag (EAFS) increases progressively with extended curing durations, while a replacement level of EAFS exceeding 20% has a detrimental effect on the compressive strength of the mortar. The curing temperature is found to be a critical factor influencing the mechanical performance of EAFS-based mortars, as high curing temperatures accelerate early-age strength development, though their impact on long-term strength is less consistent. An optimum curing temperature of about 40 °C has been identified, since it promotes both early-age and long-term strength, making it especially beneficial for applications requiring rapid strength gain. In addition, mortars cured at 40 °C and 60 °C consistently exhibit higher ultrasonic pulse velocity (UPV) values compared to the control mixture, and the steady increase in UPV with curing age reflects continuous enhancements in the internal structure and density of the EAFS-based mortars.

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REFERENCES

[1] Abdalkader, A.; Elzaroug, O. Hardened properties of recycled aggregate concrete incorporating pulverised fly ash. *AL-Mukhtar Journal of Engineering Research*, **2021**, 1(4), pp. 62-67.

[2] Abubaker, F.; Ghanim, H.; Abdalkader, A. Effect of fly ash addition on mechanical properties of concrete. *Global Journal of Advanced Engineering Technologies and Sciences (GJAETS)*, **2018**, 5(1), pp. 7-15.

[3] Dadsetan, S.; Bai, J. Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash. *Construction and Building Materials,* **2017**, 146, pp. 658-667.

[4] Xu, G., et al. Early-age hydration and mechanical properties of high-volume slag and fly ash concrete at different curing temperatures. *Construction and Building Materials*, **2017**, 149, pp. 367-377.

[5] Siddique, R. Utilization of silica fume in concrete: Review of hardened properties. *Resources, Conservation and Recycling*, **2011**, 55, pp. 923-932.

[6] Moolchandani, K. Industrial by-products in concrete: A state-of-the-art review. *Next Materials*, **2025**, 8, 100593.

[7] Proctor, D., et al. Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags. *Environmental Science & Technology, **2000**, 34*(8), 1576-1582.

[8] Brand, A.; Fanijo, E. A review of the influence of steel furnace slag type on the properties of cementitious composites. *Applied Sciences, **2020**, 10*(22), 8210.

[9] Jiang, Y., et al. Characteristics of steel slags and their use in cement and concrete: A review. *Resources, Conservation and Recycling, **2018**, 136*, 187-197.

[10] Li, Z., et al. Cementitious property modification of basic oxygen furnace steel slag. *Construction and Building Materials, **2013**, 48*, 575-579.

[11] Bougara, A.; Lynsdale, C.; Ezziane, K. Activation of Algerian slag in mortars. *Construction and Building Materials, 2009, 23*(1), 542-547.

[12] Alsadig, D.; Wagialla, K. Effect of local steel slag on compressive strength of cement mortars. *Journal of Advanced Chemical Engineering, **2018**, 8*(2), 1-5.

[13] Wang, Y.; Suraneni, P. Experimental methods to determine the feasibility of steel slag as supplementary cementitious materials. *Construction and Building Materials, **2019**, 204*, 458-467.

[14] Santamaría-Vicario, I., et al. Design of masonry mortars fabricated concurrently with different steel slag aggregates. *Construction and Building Materials, **2015**, 95*, 197-206.
[15] Pan, Z., et al. Investigating the effects of steel slag powder on the properties of self-compacting concrete with recycled aggregates. *Construction and Building Materials, 2019, 200*, 570-577.
[16] Amin, M. N., et al. Influence of mechanically activated electric arc furnace slag on compressive strength of mortars incorporating curing moisture and temperature effects. *Sustainability, **2017**, 9*(8), 1178.
[17] Abdalkader, A.; Farag, M.; Muhamed, Z. Influence of steel slag fineness and replacement level on the compressive strength of cement mortars. *Scientific Journal of Open University - Benghazi, **2024**, 5*(2), 110-121.
[18] Bougara, A.; Lynsdale, C.; Milestone, N. B. The influence of slag properties, mix parameters, and curing temperature on hydration and strength development of slag/cement blends. *Construction and Building Materials, 2018, 187*, 339-347.