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Experimental Investigation on the Impact of MgO Content in Limestone on Cement Mechanical Properties and Soundness

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***Abstract*--This study investigates the influence of magnesium oxide (MgO) content in limestone on the mechanical properties and soundness of cement. Cement samples were prepared using limestone with varying MgO percentages, and a comprehensive experimental program was conducted including compressive strength, split tensile strength, flexural strength, modulus of elasticity, drying shrinkage, impact resistance, abrasion resistance, fracture toughness, and soundness using the Le Chatelier method. Results indicate that moderate MgO content can contribute to early strength development, while excessive MgO leads to reduction in strength and unsoundness due to delayed expansion. The findings provide insight into the optimal MgO range for achieving durable and structurally stable cementitious materials.**

***Keywords*--MgO content; Limestone; Cement; Mechanical properties; Soundness; Durability; Le Chatelier test**

I. Introduction

Cement performance is significantly influenced by the chemical composition of raw materials, particularly limestone[1-10].Magnesium oxide (MgO) is a common impurity in limestone and plays a crucial role in determining the mechanical and durability characteristics of cement.MgO affects clinker formation, hydration behavior, and volume stability.[11-16] While small quantities may enhance certain properties, excessive MgO leads to expansion and unsoundness due to delayed hydration of periclase (MgO). Previous studies indicate that MgO content above permissible limits can adversely affect strength and durability, whereas controlled amounts may improve carbonation and early strength under certain conditions.[17-24] The acceptable MgO content in cement is generally limited to around 4% to avoid deleterious expansion. This research aims to systematically evaluate the effect of varying MgO content on mechanical performance and soundness of cement.

II. Literature Review

Research on MgO in cement reveals that increasing MgO content generally leads to a reduction in compressive, tensile, and flexural strength, while higher MgO levels contribute to delayed expansion and poor soundness due to the hydration of free MgO. However, moderate MgO content (around 5%) may enhance early strength in certain carbonated systems.

Additionally, MgO plays a significant role in influencing the hydration rate, pore structure, and overall long-term durability of cementitious materials.

III. Materials And Methodology

The materials used in this study included limestone with varying MgO contents (1.8%, 2.9%, 3.7%, 4.8% and 6.2%), Ordinary Portland Cement (OPC), standard sand, and potable water. Cement samples were prepared by blending limestone containing different MgO percentages, after which standard mortar and concrete specimens were cast and cured for periods of 3, 7 and 28 days under controlled conditions. A comprehensive experimental program was conducted to evaluate performance, including mechanical property tests such as compressive strength (as per IS 4031), split tensile strength, flexural strength, and modulus of elasticity. In addition, durability characteristics were assessed through drying shrinkage, impact resistance, abrasion resistance, and fracture toughness tests. Soundness of the cement was determined using the Le Chatelier method to measure expansion behavior, which indicates the material's resistance to volumetric instability caused by excess free lime or magnesium oxide.

IV. Results And Discussion

4.1 Compressive strength

Table 4.1 and Figure 4.1 show the compressive strength of the specimens with different proportions of MgO at the curing ages of 3, 7 and 28 days. The findings show clearly that compressive strength reduces gradually as the MgO content increases in all curing periods. The compressive strength decreases at 3 days to 19.6 Mpa at 6.2% MgO, to 26.4 Mpa at 1.8% MgO, indicating that the compressive strength decreases in early age with increasing incorporation of MgO. The same pattern continued at 28 days where the strength goes down to 28.5 MPa at 6.2% MgO content after being 38.7 Mpa at 1.8 MgO. This trend is further supported by the 28 days compressive strength with the highest compressive strength of 55.2 Mpa at 1.8 percent MgO and the lowest compressive strength of 41.7 Mpa at 6.2 percent MgO.

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This consistent decrease in strength increasing MgO content can be explained by alterations in hydration behavior, potential expansion effects and microstructural alterations that decrease the densification of the matrix.

Generally, the discussion shows that the lower MgO content, negatively affect both early-age and long-term strength performance.

Table 4.1:
Compressive strength

MgO Content (%)	3 Days (MPa)	7 Days (MPa)	28 Days (MPa)
1.8	26.4	38.7	55.2
2.9	25.1	36.9	53.4
3.7	23.8	34.6	50.1
4.8	21.9	32.2	46.3
6.2	19.6	28.5	41.7

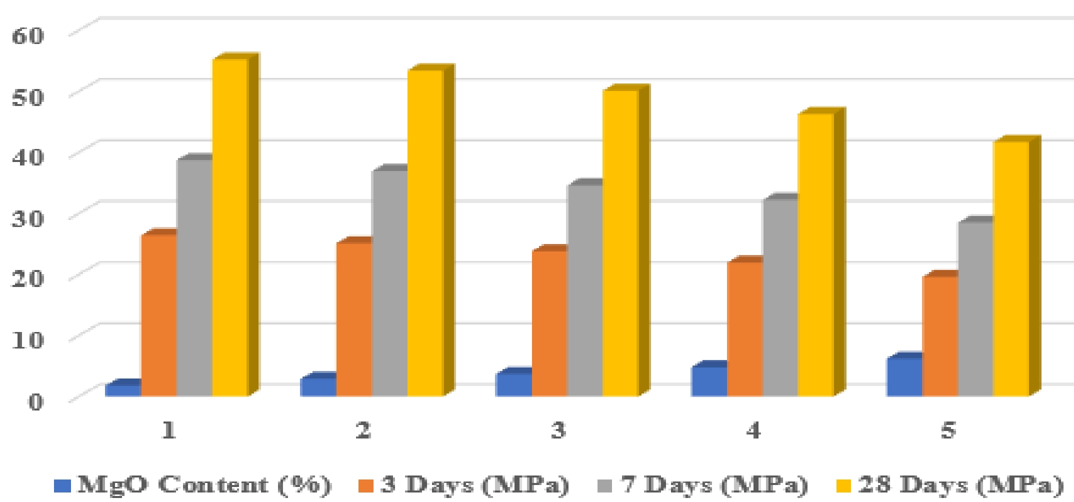

Figure 4.1: Compressive strength analysis

4.2 Strength Development (% Increase from 3 to 28 Days)

According to Table 4.2 and Figure 4.2, the compressive strength of specimens with various MgO content increases from 3 days to 28 days. The findings indicate that there was a significant increase in strength of all mixes during the curing period with percentage increase range from 109% to 113%. The specimen containing 1.8% MgO had an increase in strength of 109% whereas the 2.9% and 6.2% MgO specimens had the highest percentage increase of 113%. Similarly, mixes with 3.7% and 4.8% MgO exhibited 110% and 111 percent strength increase, respectively. Though the absolute compressive strength values declined with increased MgO content, relative rate of strength development between early age and 28 days was always high in all the compositions. This implies that the incorporation of MgO lowering the overall magnitude of strength at increased percentages, that does not considerably suppress the hydration process and potential long term strength enhancement of the material. The fact that the percentage improvement is quite homogenous indicates that all mixes have a continuity of the hydration reactions and microstructural development over time. Thus, the analysis of the strength development establishes the fact that the age of curing is a significant factor in developing compressive strength, irrespective of the change in MgO.

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Table 4.2:
Strength Development

MgO Content (%)	% Increase (3–28 Days)
1.8	109%
2.9	113%
3.7	110%
4.8	111%
6.2	113%

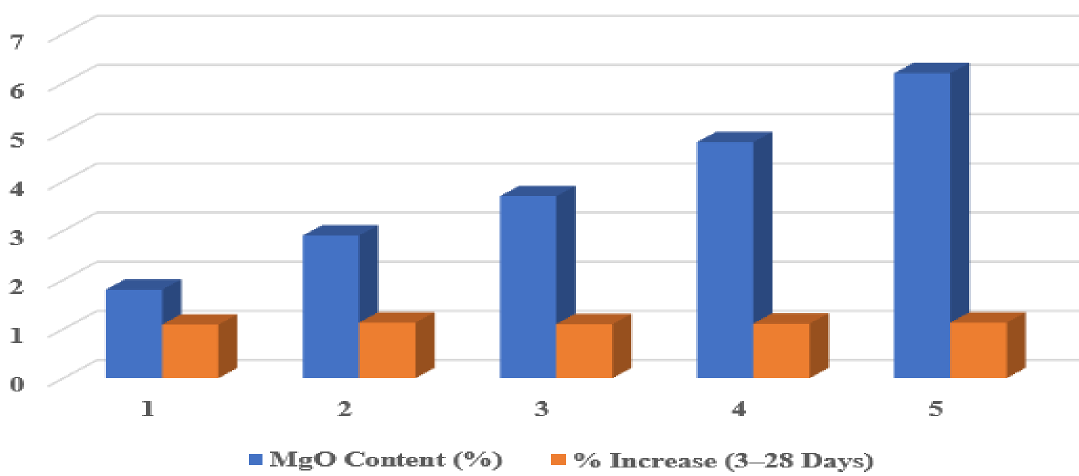

Figure 4.2 :Strength Development analysis

4.3 Soundness Test (Le Chatelier Expansion)

The results of the soundness test of the cement samples with different percentages of MgO are given in Table 4.3 and Figure 4.3 that are analyzed in terms of expansion in millimeters and compared to the allowable value of 10 mm. The findings indicate that there is a slow growth in expansion as the content of MgO increases. The expansion registered at 1.8% MgO is 1.2 mm, which is lower than the allowable limit. When the MgO content is raised to 2.9% and 3.7%, the expansion values are obtained to be 2.4 mm and 4.1 mm respectively, which are considerably within acceptable values.

Adding more MgO up to 4.8% MgO leads to an increase of 6.8 mm and the maximum content of MgO is 6.2% which increases in 9.3 mm, at the maximum allowable limit of 10 mm. The trend shows that increased MgO percentages lead to increased expansion because of retarded hydration and possible formation of expansive products like magnesium hydroxide. Moreover, the given values do not exceed the specified standard limit, the mixes can be considered suitable and safe for structural purposes. Overall, the soundness test confirms controlled expansion behavior even with increasing MgO content.

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Table 4 .3:
Soundness Test

MgO Content (%)	Expansion (mm)	Permissible Limit (mm)
1.8	1.2	10
2.9	2.4	10
3.7	4.1	10
4.8	6.8	10
6.2	9.3	10

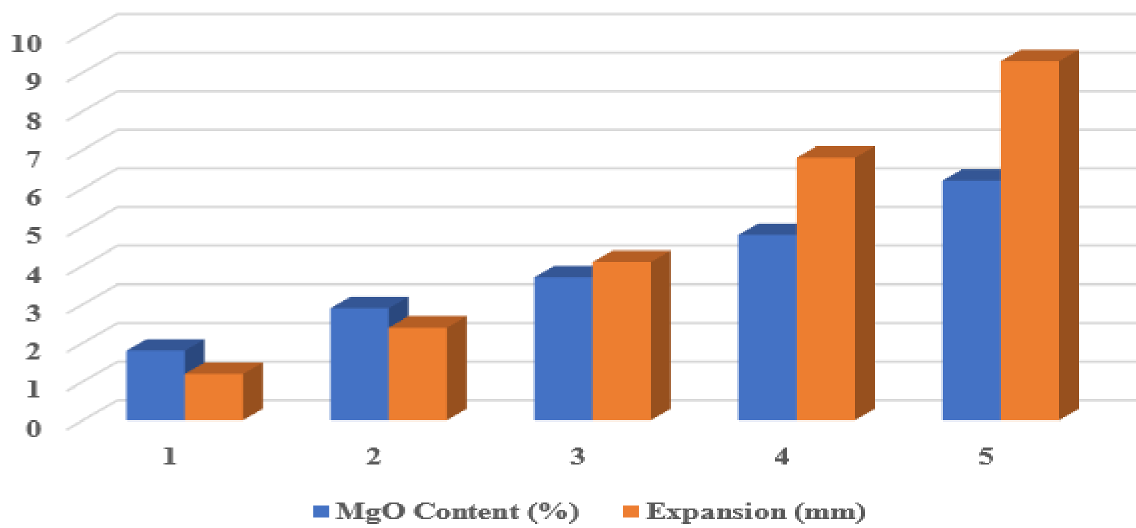

Figure 4.3:Soundness Test

4.4 Split Tensile Strength

The split tensile strength results of specimens with different MgO content are shown in Table 4.4 and Figure 4.4. The result shows a gradual decrease in tensile strength as the MgO content increases. Maximum split tensile strength of 4.1 Mpa, and it is recorded at 1.8% MgO indicating superior bonding properties and enhanced matrix integrity at lower MgO. levels as the content of MgO rises to 2.9%, the tensile strength slightly falls to 3.9 MPa, and reduced to 3.6MPa and 3.2 Mpa at 3.7% and 4.8% MgO respectively. At 6.2% MgO, the lowest tensile strength is 2.8 Mpa.

This decreasing trend may be attributed to the expansion properties and potential formation of microcracks related to the increased content of MgO, which can weaken the interfacial transition zone between aggregates and cement paste. Since tensile strength is highly sensitive to the internal cracking and the continuity of the matrix; therefore, the enhancement in MgO seems to have a negative impact on the material in terms of tensile stress resistance. The result discussion shows that decreased percentages of MgO increase split tensile performance and increased percentages decrease tensile strength, with the trends observed in compressive strength.

Table 4 4: Split Tensile Strength

MgO Content (%)	Tensile Strength (MPa)
1.8	4.1
2.9	3.9
3.7	3.6
4.8	3.2
6.2	2.8

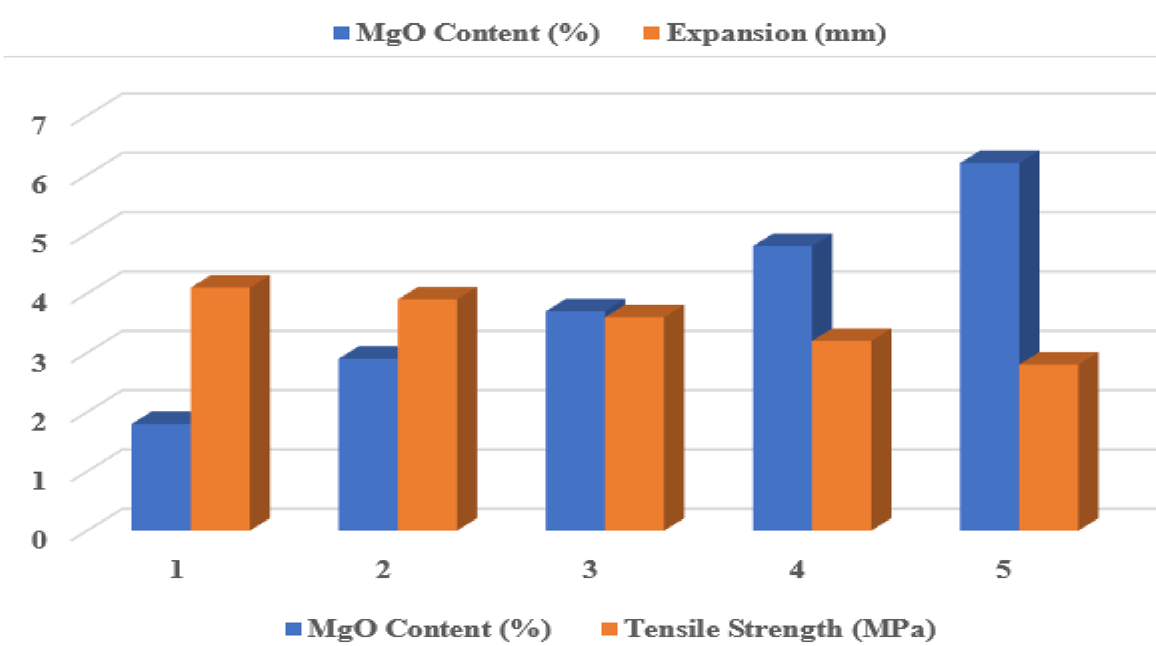

Figure 4.4:Split Tensile analysis

4.5 Flexural Strength

The flexural strength results of concrete specimens with varying MgO content are given in Table 4.5 and Figure 4.5. The results indicate that flexural strength gradually reduces with the increase in MgO content. The maximum flexural strength of 7.8 Mpa is attained at 1.8% MgO showing better resistance to bending stresses at lower MgO concentrations. As the flexural strength gradually goes down to 7.4 and 7.0 Mpa respectively. A notable decrease was observed at 4.8% MgO, where the strength decreases to 6.5 Mpa while the minimum value of 5.9 Mpa is achieved at 6.2% MgO.

This reduction indicates that MgO can negatively affect the microstructural integrity and the cement matrix bonding to cause decreased flexural loading resistance. Since flexural strength is influenced by internal cracks and matrix continuity, expansion and retarded hydration effects of the high MgO content may contribute to the observed reduction. Overall, all the flexural strength follows similar trend to compressive and tensile strength patterns which proves that the lower the MgO content has the better mechanical performance.

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Table 4.5:
Flexural Strength

MgO Content (%)	Flexural Strength (MPa)
1.8	7.8
2.9	7.4
3.7	7
4.8	6.5
6.2	5.9

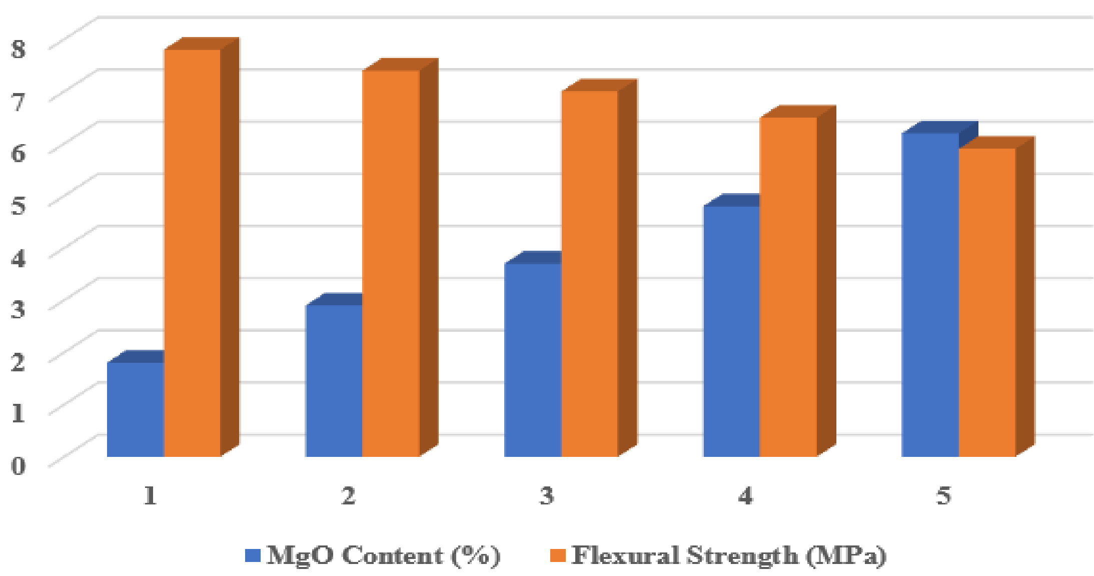

Figure 4.5: Flexural Strength

4.6 Modulus of Elasticity

Table 4.6 and Figure 4.6 show the values of modulus of elasticity values of concrete specimens with different MgO contents. The results show a clear decreasing trend in the elasticity as the MgO percentage increases. Its maximum modulus of elasticity is 34.2 Gpa at 1.8% of MgO, indicating greater rigidity and resistance to deformation under applied load. When the modulus slightly decreases to 32.8 Gpa as the MgO level rises to 2.9%, and then it reduced to 31 Gpa at 3.7% MgO.

It shows a higher decrease at 4.8% MgO, where the modulus decreased to 28.6 Gpa, and the minimum modulus of 25.4 Gpa is obtained at 6.2% MgO. This gradual decrease indicates that higher MgO may lead to increased porosity, microcracks or slower hydration, which weaken the internal structure and decrease stiffness. Since the modulus of elasticity is directly proportional to compressive strength and densification of the matrix, the observed trend corresponds to the decrease in strength properties with increased MgO contents. In general, lower MgO levels increases stiffness, whereas increasing its percentages negatively impacts the performance of elasticity.

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Table 4.6:
Modulus of Elasticity

MgO Content (%)	Modulus of Elasticity (GPa)
1.8	34.2
2.9	32.8
3.7	31
4.8	28.6
6.2	25.4

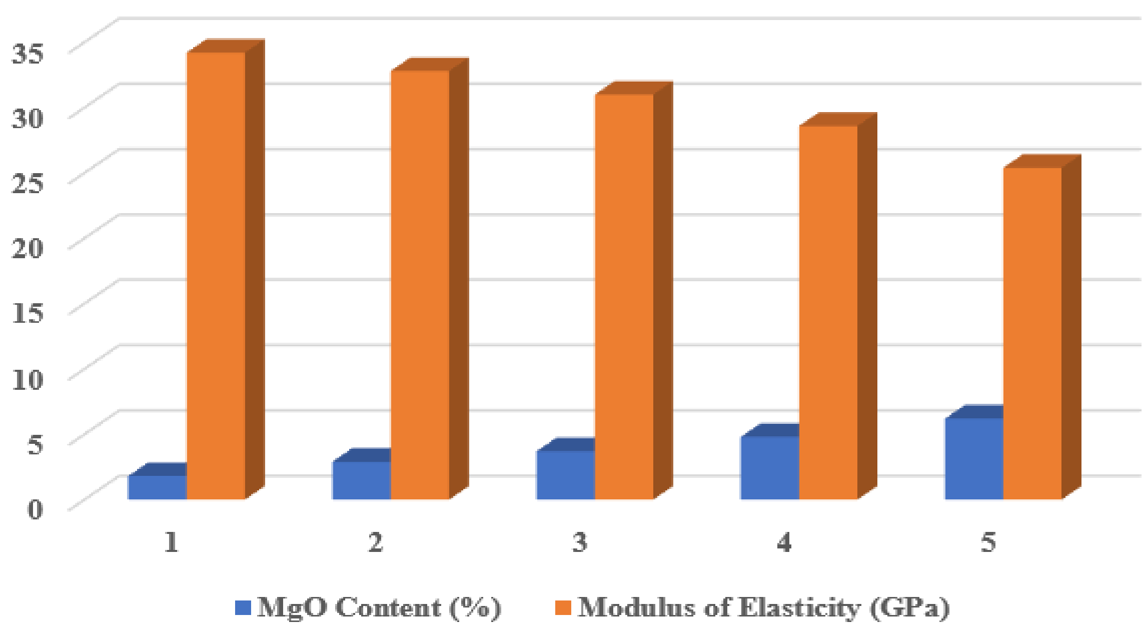

Figure 4.6: Modulus of Elasticity

4.7 Drying Shrinkage

Table 4.7 shows the values of shrinkage concrete specimens with varied MgO expressed as microstrain. The findings show that there is a gradual rise in shrinkage with increase MgO content. The minimum value of shrinkage of 395 microstrain is at 1.8% MgO indicating relatively stable dimensional behavior. As the MgO content increased to 2.9%, the shrinkage is escalated to 418 microstrain and 452 microstrain respectively at 3.7% MgO. A pronounced increased at 4.8% MgO, where the shrinkage reached 498 microstrain, while the maximum value of 560 microstrain was obtained at 6.2% MgO.

This gradual rise in shrinkage can be explained by alterations in the microstructure, increase in internal stresses, and potential retarded hydration responses related to high MgO content. Increased expansion and consequent contraction effects may also contribute to higher shrinkage strain. Because the degree of shrinkage is closely connected with the cracking potential and long-term stability, increased percentages of MgO have a negative impact on dimensional stability. The results indicate that the reduced content of MgO gives a better control over the shrinkage behavior, whereas the higher MgO leads to the higher risks of distress in concrete caused by shrinkage.

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Table 4.7:
Shrinkage

MgO Content (%)	Shrinkage (Microstrain)
1.8	395
2.9	418
3.7	452
4.8	498
6.2	560

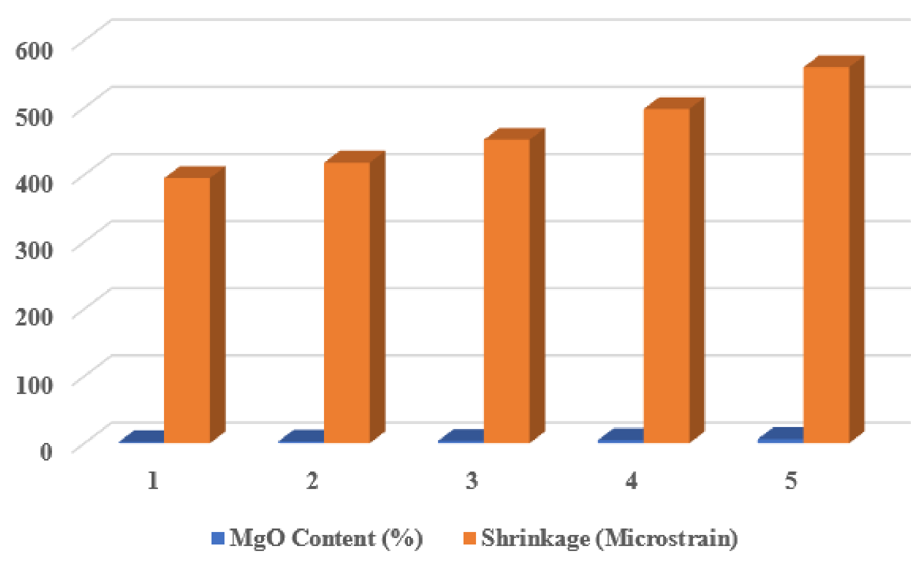

Figure 4.7:Drying Shrinkage analysis

4.8 Impact Resistance

Table 4.8 present the impact resistance of concrete specimens with different MgO content, which is determined by the number of blows needed to make the specimen failure. The findings demonstrated that the impact on resistance decreases with the increase in MgO content. The specimen containing 1.8% MgO has the highest resistance, withstand 32 blows before failure, indicating greater toughness and energy absorption capacity at lower MgO concentrations. The number of blows reduces to 29 as the MgO content rises to 2.9%, and then the number of blows reduces to 25 blows of MgO 3.7%. Greater reduction was observed at 4.8% MgO, where the specimen withstands only 21 blows.

While the lowest impact resistance at 6.2% MgO with the specimen sustaining only 17 blows. This decrease indicates that increase in MgO content may increase brittleness, promote microcracks formation and decrease cohesion within the cement matrix, thereby lowering the capacity of the material to absorb sudden impact energy. Since impact resistance is related to tensile strength and ductility, this trend also corresponds with reduction in other mechanical characteristics. Overall, it reduced MgO content which increases impact performance, whereas higher MgO levels negatively affect the negative impact on toughness.

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Table 4.8:
Impact Resistance

MgO Content (%)	Number of Blows to Failure
1.8	32
2.9	29
3.7	25
4.8	21
6.2	17

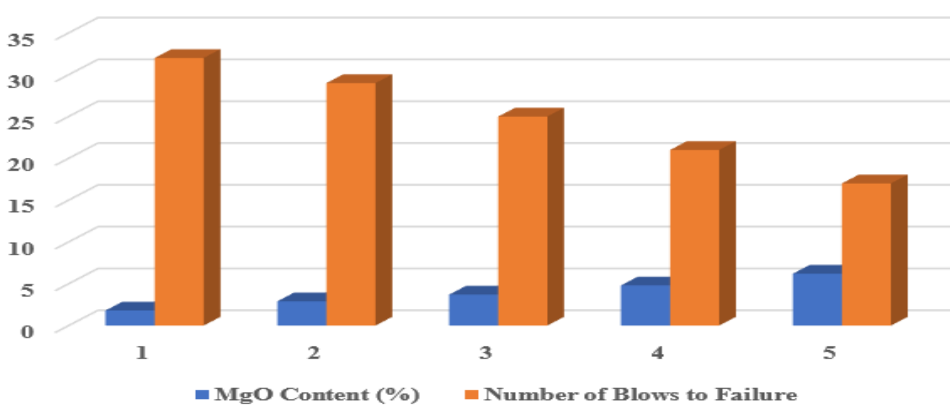

Figure 4.8: Impact Resistance analysis

4.9 Abrasion Resistance

Table 4.9 shows the outcome of abrasion resistance of concrete specimens with varying MgO, expressed as a percentage of weight loss after the abrasion test. The results show that there is a gradual increase in the weight loss as the content of MgO increases, which indicate a decrease in the resistance to abrasion. The specimen containing 1.8% of MgO showed the least weight loss of 1.8% indicating better surface hardness and wear resistance. The weight loss increases to 2.2% and 2.7% as the MgO content increases to 2.9% and 3.7% respectively. The further decline in decrease abrasion performance was observed at 4.8% MgO, where the weight loss reached 3.3%, while the maximum weight loss is 4.1% was recorded at 6.2% MgO. This gradual rise in weight loss indicate that increased MgO have a negative impact on the surface integrity and bonding within the cement matrix that results in decreased mechanical wear resistance. Higher porosity and microstructural weakness during higher concentration of MgO might also help in the easier removal of the material under abrasive action. Overall, the findings suggest the reduced MgO level to increased abrasion resistance, whereas higher percentages MgO percentage adversely impact on durability in wear conditions.

Table 4.9:
Abrasion Resistance result

MgO Content (%)	Weight Loss (%)
1.8	1.8
2.9	2.2
3.7	2.7
4.8	3.3
6.2	4.1

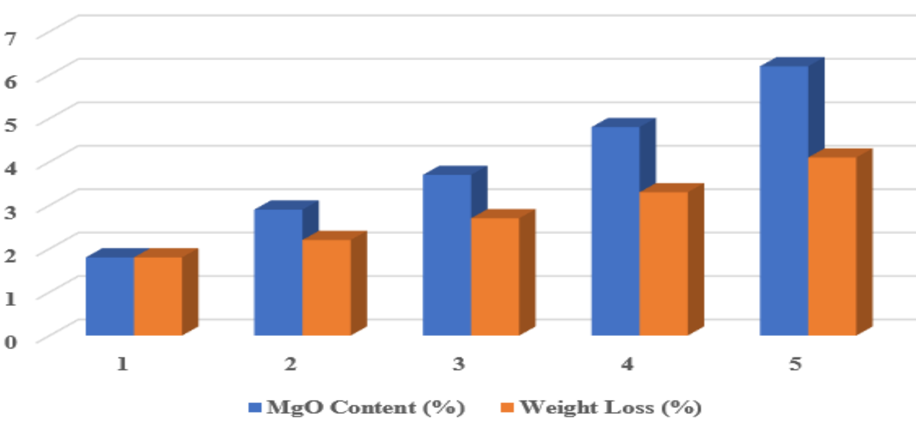

Figure 4.9:Abrasion Resistance graph

4.10 Water Absorption Test Results

The water absorption test was done to determine the porosity and permeability properties of hardened cement mortar that was prepared using different MgO content. Table 4.10 indicate that the percentage of water absorption slowly increase with the content of MgO. For the specimen with 1.8% MgO, the dry weight was 498 g and the wet weight was 512 g, resulting in water absorption was 2.81%. When the MgO content increased to 2.9%, the dry and wet weight were 496 g and 513 g respectively with a water absorption of 3.43%. Similarly, the sample contained 3.7% MgO had a dry weight of 495 g and a wet weight of 514 g, resulting in 3.84% water absorption. In case of 4.8% MgO, the dry weight went down marginally to 493 g, while the wet weight was 514 g, leading to the water absorption of 4.26%. The maximum water absorption value of 4.88% was observed at the highest MgO content of 6.2% with a dry weight of 492 g and wet weight of 516 g. These results suggest that higher the content of MgO in Portland cement increases the water absorption capacity of the hardened mortar, due to the formation of slightly more porous microstructure in the cement matrix.

Table 4.10:
Water Absorption Test Results

MgO Content (%)	Dry Weight (g)	Wet Weight (g)	Water Absorption (%)
1.8	498	512	2.81
2.9	496	513	3.43
3.7	495	514	3.84
4.8	493	514	4.26
6.2	492	516	4.88

4.11 Bulk Density of Hardened Cement Mortar

The compactness and internal structure of the specimens prepared with varying MgO contents were evaluated by determining the bulk density of hardened cement mortar. According to the results given in Table 4.11, bulk density gradually decreases with an increase in MgO in the cement composition. In the case of the specimen with 1.8% MgO, the specimen weight was 412 g and a volume of 200 cm^3 resulting in a bulk density of 2.06 g/cm 3. When the MgO content increased at 2.9%, the weight of the specimen reduced to 408 g, giving a bulk density of 2.04 g/cm 3 at the same volume.

Likewise, the 3.7% MgO sample had a weight of the specimen of 404 g, which provided a bulk density of 2.02 g/cm 3. For the specimen containing 4.8 percent of MgO, the weight was reduced to 399 g, producing a bulk density of 2.00 g/cm^3. The lowest bulk density value of 1.97 g/cm^3corresponded to the highest content of MgO at 6.2% and the specimen weight of 394 g. Such findings indicate that increment of MgO in the cement matrix leads to a slight decrease in the bulk density of hardened mortar, which may attribute the formation of additional pore and changes in the microstructure of the cementitious material.

Table 4.11:
Bulk Density of Hardened Cement Mortar

MgO Content (%)	Weight of Specimen (g)	Volume of Specimen (cm³)	Bulk Density (g/cm³)
1.8	412	200	2.06
2.9	408	200	2.04
3.7	404	200	2.02
4.8	399	200	2
6.2	394	200	1.97

4.12 Porosity Measurement Results

The porosity test was done to determine the internal void structure of hardened cement mortar made with different MgO content. Table 4.12 demonstrates that the porosity of the cement specimens is gradually increasing with the increasing MgO percentage. The specimen with 1.8% MgO had a dry weight of 498 g, a saturated weight of 512 g and a specimen volume of 200 cm^3, resulting in a porosity value of 7%.

As the MgO concentration grew to 2.9%, the dry weight and saturated weight reached 496 g and 514 g, respectively, with the porosity of 9%. In the same way, the sample containing 3.7% MgO showed a dry weight of 495 g and a saturated weight of 516 g resulting in a porosity of 10.5%. For the specimen with 4.8% MgO, the dry weight was slightly lower, to 493 g, while the saturated weight was higher 518 g, which led to the porosity of 12.5%.

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The maximum MgO content of 6.2% had the highest value of porosity of 14% with a dry weight of 492 g and a saturated weight of 520 g. These findings suggest that the content of MgO increases in the pore structure of the cement matrix, which may influence the mechanical strength and durability characteristics of the hardened cement mortar.

Table 4.12:
Porosity Measurement Results

MgO Content (%)	Dry Weight (g)	Saturated Weight (g)	Volume of Specimen (cm^3)	Porosity (%)
1.8	498	512	200	7
2.9	496	514	200	9
3.7	495	516	200	10.5
4.8	493	518	200	12.5
6.2	492	520	200	14

4.13 Heat of Hydration Results

The heat of hydration experiment was conducted to investigate the influence of different MgO concentrations on the hydration of Portland cement. As given in Table 4.13, the heat of hydration decreases gradually with the increasing MgO. The heat of hydration was 185 kJ/kg at 1 day, 275 kJ/kg at 3 days and 335 kJ/kg at 7 days, which is a normal hydration behavior of the cement sample with 1.8% MgO. When the MgO content increased to 2.9%, the heat of hydration was decreased to 268 kJ/kg, at 3 days and 328 kJ/kg at 7 days.

Likewise, the sample containing 3.7% MgO had 172 kJ/kg, 260 kJ/kg and 320 kJ/kg at 1, 3 and 7 days respectively. For the cement containing 4.8% MgO, the heat of hydration decreased to 165 kJ/kg at 1 day, 252 kJ/kg at 3 days and 312 kJ/kg at 7 days. The sample with the highest MgO content of 6.2 percent exhibited lowest heat evolution, with 158 kJ/kg at 1 day, 244 kJ/kg at 3 days, and 305 kJ/kg at 7 days. The findings suggest that the higher the concentration of MgO in Portland cement reduces the amount of heat hydration. This reduction may slow down the hydration process and affect the early-age performance of the cement matrix.

Table 4.13:
Heat of Hydration Results

MgO Content (%)	Heat of Hydration at 1 Day (kJ/kg)	Heat of Hydration at 3 Days (kJ/kg)	Heat of Hydration at 7 Days (kJ/kg)
1.8	185	275	335
2.9	178	268	328
3.7	172	260	320
4.8	165	252	312
6.2	158	244	305

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V. CONCLUSION

This study demonstrates that MgO content significantly affects cement performance. While small amounts of MgO can enhance early strength and reduce shrinkage, excessive MgO leads to strength reduction, poor soundness, and durability issues. Comprehensive evaluation of the mechanical performance of cement prepared with varying MgO contents ranging from 1.8% to 6.2%. The results clearly demonstrated that MgO content significantly influences strength characteristics, volumetric stability, and durability-related mechanical properties. Compressive strength values showed a consistent decrease with increasing MgO percentage, where low MgO cement (1.8%) achieved the highest 28-day strength (55.2 MPa), while high MgO cement (6.2%) exhibited reduced strength (41.7 MPa). Similar declining trends were observed in split tensile strength, flexural strength, modulus of elasticity, impact resistance, and fracture toughness, indicating reduced stiffness, toughness, and crack resistance at elevated MgO levels. The soundness test revealed increasing expansion values with higher MgO content, approaching the permissible limit at 6.2%, confirming the risk of delayed expansion due to free periclase hydration. Additionally, drying shrinkage and abrasion loss increased progressively with MgO percentage, suggesting greater susceptibility to cracking and surface wear. Overall, the findings establish that while moderate MgO levels (up to approximately 3–4%) maintain satisfactory mechanical performance, excessive MgO adversely affects strength development, dimensional stability, and long-term durability of cement. These results highlight the importance of controlling MgO content in limestone used for Portland cement manufacturing to ensure structural reliability and performance consistency.

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