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Research Article

Effects of Alternative Binder and Aggregate Use on the Compressive Strength of Concrete

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ABSTRACT

The use of industrial wastes in concrete production is of significant importance in reducing environmental impacts and lowering costs. In this study, concrete mixtures were designed by using olivine minerals as a substitute for Portland cement (PC), chromite powder as fine aggregate, and ferrochromium slag as coarse aggregate. The effects of different binder and aggregate ratios on the compressive strength of the concrete were examined after a 7-day curing period. Experimental results showed that mixtures with 5% olivine substitution achieved the highest compressive strength of 22.30 MPa, particularly in mixtures with a cement dosage of 500 kg/m³. This result indicates that the low water/cement ratio and the addition of olivine contribute to increased early-age strength. Furthermore, increasing the chromite powder content to 20% in mixtures with a water/cement ratio of 0.61 led to an 11.7% increase in compressive strength, demonstrating the positive impact of chromite powder on the mechanical performance of the concrete. These findings highlight that cement replacements and aggregate types can significantly affect the mechanical properties of concrete, emphasizing the need for careful selection of both material compositions.

1. Introduction

Since the early 20th century, rapid industrialization has contributed to the progress of civilization while also bringing about environmental issues [1]. This situation has increased the importance of recycling in order to reduce the negative environmental impacts of waste materials and ensure more efficient use of resources [2]. The sustainable utilization of waste materials provides both environmental and economic benefits, particularly in the construction industry [3]. In Turkey and worldwide, the disposal or storage of waste is considered one of the major environmental challenges to be faced in the future [4].

The environmental impacts and high costs of Portland cement have encouraged the investigation of alternative binder materials in concrete production [5]. In this context, the use of industrial waste contributes to objectives such as reducing CO_2 emissions, limiting harmful chemical additives, and decreasing the consumption of natural resources [6], [7], [8]. The utilization of waste materials in concrete production is a crucial step to reduce environmental pollution and lower production costs [9]. Numerous studies have been conducted in the literature on the use of industrial by-products, such as silica fume, blast furnace slag, and fly ash, in concrete production [10], [11].

Chromite ore is a material widely used in the metallurgy and mining industries, and various waste materials are produced during its processing [12], [13]. The use of chromite ore and its processing by-products, such as chromite powder and chromite slag [14], in concrete production enhances environmental sustainability and has the potential to improve the physical and mechanical properties of concrete. In the literature, there are studies indicating that chromium compounds enhance the engineering properties of concrete. For example, Aygün et al. [15] reported that the addition of chromite ore and other metal oxides (Fe_2O_3, TiO_2, $FeO(OH)nH_2O$, $FeCO_3$, PbS, Cr_2O_3, MnO_2) to concrete increases the neutron and gamma radiation absorption capacity and achieves strength up to 30 MPa.

The use of olivine in refractory materials has also become another notable topic in the construction industry. Acar [16] stated that olivine samples obtained from the chromite processing plant were used directly without any pre-treatment and exhibited acceptable shrinkage properties at high temperatures, indicating their potential for use in the production of refractory materials. With these characteristics, olivine is becoming a valuable material that can be utilized in concrete production.

However, there are limited studies in the literature on the combined use of olivine and chromite powder in concrete production. In response to this gap, this study investigates the use of olivine, chromite powder, and ferrochromium slag as replacements in specific proportions to enhance the compressive strength of concrete. This research aims to contribute to the effective use of waste materials in concrete production and improve the strength properties of concrete.

The study seeks to provide significant findings in terms of both environmental sustainability through the utilization of waste and the enhancement of mechanical properties in the construction industry's concrete.

2. Material and Method

2.1. Materials

In this study, CEM I/42.5R Portland cement with a specific gravity of 3.06 was used as the binder material. The specific gravity of the olivine mineral, which was substituted for cement in various proportions, was found to be 3.30. The XRF analysis results of both the cement and olivine are presented in Table 1.

For the preparation of concrete samples, ferrochromium slag was used as the coarse aggregate and chromite powder as the fine aggregate. The specific gravity and water absorption of the aggregates were determined according to ASTM C128 [17], while the loose and compacted bulk densities were measured in accordance with ASTM C29 [18]. The specific gravity of the ferrochromium slag was found to be 2.86, with a water absorption rate of 3.63% and a moisture content of 0.36%. Its loose and compacted bulk densities were 1590 kg/m³ and 1800 kg/m³, respectively. The specific gravity of the chromite powder was determined as 4.94, and its loose and compacted bulk densities were 2520 kg/m³ and 2930 kg/m³, respectively. The granulometric curves of the fine and coarse aggregates are presented in Figure 1. Images of the materials used in the study are shown in Figure 2.

Table 1. XRF analysis results of cement and olivine samples: Oxide composition distribution

Oxide (%)	Cement	Olivine
CaO	63.0	1.6
SiO_2	18.7	34.8
MgO	1.5	48.0
Fe_2O_3	3.7	12.7
Al_2O_3	4.8	1.0
Cr_2O_3	-	0.5
Na_2O	0.3	< 0.11
K_2O	0.6	-
SO_3	2.9	-
MnO	-	0.2
P_2O_5	-	0.4
LOI	3.7	-

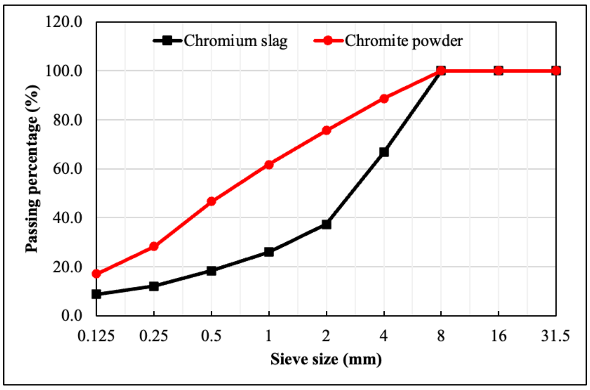

Figure 1. Granulometric curves of the aggregates used in the mixtures

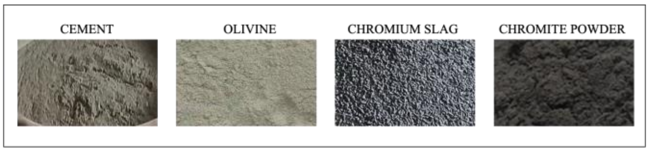

Figure 2. Images of the materials used in the experimental mixtures

2.2. Method

In the experimental study, concrete mixtures were prepared using Portland cement, olivine, chromite powder, and chromium slag. Olivine was used as a partial replacement for Portland cement at a volume ratio of 5%. In addition, chromite powder was incorporated into the mixtures by replacing chromium slag at volume-based replacement ratios of 0%, 10%, and 20%, respectively.

The C20 concrete class, which is commonly used in the construction industry and compliant with the TS EN 206-1 [19] standard, has been determined as the target compressive strength. In this study, the mix proportions were calculated according to the TS 802 [20] standard, and the relevant values are presented in Table 1. Fresh concrete samples were removed from molds with dimensions of 10×10×10 cm one day after casting and placed in a water curing pool. After a 7-day curing period, the samples were subjected to compressive strength testing. The compressive strength tests were conducted in accordance with TS EN 12390-3 [21] standard, with the testing machine applying a uniform load to the samples in the axial direction at a rate of 3 kN/s.

Table 2. Mix proportions of the components used in the experimental design

Mix No.	Olivine (%)	PC (%)	Chromium slag (%)	Chromite powder (%)	Water-Binder	Cement content (kg/m³)
Mix 1	0	100	100	0	0.61	377
Mix 2	5	95	90	10	0.61	377
Mix 3	5	95	80	20	0.61	377
Mix 4	5	95	80	20	0.46	504
Mix 5	5	95	80	20	0.41	561
Mix 6	5	95	80	20	0.41	500

3. Results and Discussion

3.1. Effect of mix components on compressive strength

3.1.1. Binder content and ratio

The binder contents and ratios are among the key factors determining the compressive strength of concrete [22]. Cement is widely used as the primary binder material in concrete [23]. The cement content typically contributes directly to the strength of the concrete [24], [25]. However, excessive increases in cement content can negatively affect the performance of concrete [25]. On the other hand, partial replacement of cement can be beneficial both economically and environmentally [27]. In this context, the experiments conducted with 5% olivine replacement have revealed significant results affecting the strength of concrete, depending on the cement dosage. This observed effect of olivine on compressive strength can be better understood by considering the physical and chemical characteristics of olivine-derived nano silica reported in recent studies. For instance, research by Oesman and Haryadi [28] demonstrated that amorphous silica extracted from ground olivine via sulfuric acid dissolution forms particles ranging from 1 to 10 μm, influenced by acid concentration and temperature during synthesis. Although these particles were larger than the optimal nano scale (<0.1 μm) for high-performance concrete, the presence of reactive siloxane (Si–O–Si) bonds suggests a notable binding potential. This supports the idea that olivine replacement, even at low proportions, can contribute positively to the binder matrix through its reactive silica content, impacting early strength development and hydration kinetics.

Figure 3 shows the 7-day compressive strengths of the mixtures. In the mixtures with cement dosages of 377, 504, and 500 kg/m³, the replacement of 5% of cement with olivine resulted in higher compressive strengths compared to the mixtures containing 100% cement. In each of these mixtures, it was observed that the replacement of cement with olivine improved the performance of the concrete. This finding suggests that replacing cement with olivine in specific proportions can enhance the strength of concrete. Particularly, at low and medium cement dosages, it was found that olivine replacement could optimize the compressive strength of the concrete, which aligns with previous findings emphasizing the beneficial behavior of olivine in cementitious systems under varying conditions [29]. Additionally, even outside of Portland-based systems, Mg-rich olivine has shown significant reactivity and binding potential — for instance, in phosphate cement systems, olivine dissolution up to 57% was achieved under acidic conditions, highlighting its capacity as a viable reactive mineral [30].

However, when the cement dosage was increased to 561 kg/m³ and 5% olivine was used, it was experimentally observed that the resulting compressive strength decreased by 34.3% compared to the mixtures containing 100% cement. This result suggests that as the cement content increases, the potential for replacement materials, such as olivine, to improve the strength of concrete may be limited. High cement dosages can affect the hydration process of concrete, potentially restricting the capacity of replacement materials to contribute effectively. This highlights the critical role of binder ratios in optimizing the strength of concrete and indicates that replacement materials may only be effective at specific cement dosages.

In conclusion, binder contents and ratios are factors that directly affect the compressive strength of concrete. Proper selection of cement dosage and replacement materials is essential to optimize the early strength and long-term performance of concrete. These experimental findings serve as an important guide for determining the optimal proportions of cement and replacement materials.

3.1.2. Aggregate type, content, and size

The type of aggregate [31], particle size [32], and specific gravity [33] are important parameters that directly affect the microstructure and mechanical strength of concrete [34]. In the experiments, the specific gravity of the ferrochromium slag used as aggregate was 2.86, while the specific gravity of the chromite powder was determined to be 4.94. These values indicate that chromite powder has the potential to form a denser and more compact structure.

When the experimental results were examined, the compressive strength of the samples containing only ferrochromium slag was measured at 9.16 MPa. However, significant improvements in the mechanical performance of the concrete were observed when chromite powder was added as fine aggregate. In the mix containing 10% chromite powder, the strength increased by 6.98%, reaching 9.80 MPa, while in the mix containing 20% chromite powder, the strength increased by 11.7%, reaching 10.23 MPa. This indicates that chromite powder better integrates with the binder matrix, forming a denser internal structure and providing a strengthening effect.

In mixtures where the proportions of ferrochromium slag and chromite powder were kept constant, but the cement content was increased and the water/cement ratio was reduced, the effect of aggregate type and size became more pronounced. In the mixture with 504 kg/m³ of cement, the compressive strength was measured at 13.00 MPa, indicating that the aggregates worked harmoniously with the cement to optimize the strength. However, when the cement dosage was increased to 561 kg/m³ and the water/cement ratio was reduced to 0.41, the strength of the mixture containing 80% ferrochromium slag and 20% chromite powder decreased dramatically by 53.7%, dropping to 6.02 MPa. This dramatic decrease suggests that exceeding a certain limit in the interaction of aggregates with the binder system can adversely affect mechanical strength.

On the other hand, when the cement dosage was optimized to 500 kg/m³, the strength of the mixture with the same aggregates was measured at 22.30 MPa, showing a significant increase of 270.5%. This suggests that a balanced use of coarse and fine aggregates ensures more effective functioning of the binder phase and that appropriate ratios of ferrochromium slag and chromite powder can significantly enhance the strength. Similarly, Panda et al. [35] reported that ferrochrome slag possesses excellent physico-mechanical properties, and its use as both coarse and fine aggregate resulted in concrete with satisfactory compressive strength for general-purpose applications. In a more recent study, Panda et al. [36] demonstrated that the inclusion of ferrochromium slag as coarse aggregate led to more than 20% improvement in compressive strength compared to conventional concrete. Moreover, they emphasized that chromium leaching remained minimal, even under acidic conditions, confirming both technical viability and environmental safety of ferrochrome slag in concrete production.

In conclusion, the combined use of ferrochromium slag and chromite powder positively contributes to the mechanical strength of concrete, provided that the aggregate distribution is properly optimized. The coarse structure of ferrochromium slag plays a crucial role in load-bearing by forming a skeleton, while the high specific gravity of fine chromite powder strengthens the binder matrix, enhancing strength. However, excessive binder content or improper aggregate-binder ratios can reduce the effectiveness of the aggregates, negatively impacting mechanical performance. Therefore, the use of ferrochromium slag and chromite powder in concrete production should be carefully considered to achieve an optimal aggregate-binder balance.

3.2. Effect of water/cement ratio on compressive strength

The water/cement (w/c) ratio is one of the most critical parameters of concrete in terms of cement hydration, microstructure development, and ultimate mechanical performance [37]. A high W/C ratio enhances the workability of the concrete mix [38] but can reduce strength by increasing the porosity of the matrix [39, 40]. On the other hand, a low w/c ratio can limit the efficiency of hydration [41], increasing the risk of shrinkage [42]. Experimental results clearly demonstrate the decisive influence of the water/cement ratio on concrete compressive strength.

In the experiments, the cement dosage was set at 377 kg/m³ for mixtures with a 0.61 W/C ratio, and the compressive strengths of specimens incorporating specific proportions of ferrochromium slag and chromite powder were measured as 9.16 MPa (Mix 1), 9.80 MPa (Mix 2), and 10.23 MPa (Mix 3), respectively. When the W/C ratio was kept constant, a gradual increase in strength was observed with the increasing amount of chromite powder. However, when the W/C ratio was reduced to 0.46 and the cement content was increased to 504 kg/m³, the compressive strength increased by 27.1%, reaching 13.00 MPa. This improvement can be attributed to the enhanced interaction between the increased binder phase and water, resulting in a denser internal structure.

In mixtures where the W/C ratio was reduced to 0.41, different strength trends were observed depending on the increase in cement dosage. When the cement dosage was 561 kg/m³, the compressive strength of specimens containing 80% ferrochromium slag and 20% chromite powder decreased by 53.7%, reaching 6.02 MPa. This decline can be attributed to the limitation of complete hydration of cement particles at very low W/C ratios, leading to internal stresses. Additionally, the high binder content may have restricted the mechanical contribution of aggregates, accelerating the formation of microcracks and further contributing to the strength reduction.

However, in the mixture where the W/C ratio remained at 0.41 but the cement dosage was optimized to 500 kg/m³, the compressive strength exhibited a significant increase of 270.5%, reaching 22.30 MPa. This finding suggests that while very low W/C ratios can have a positive effect at specific cement dosages, excessive cement content may negatively impact early-age strength.

In conclusion, low W/C ratios can enhance strength in certain binder and aggregate combinations; however, when combined with excessive cement dosage, they may lead to adverse effects. Determining the optimal W/C ratio is a critical design parameter to ensure the completion of the hydration process and maximize mechanical strength.

3.3. Effect of mix design on application areas

In this study, only 7-day compressive strength tests were conducted. This parameter is a crucial indicator for evaluating the early-age performance of concrete. However, examining other properties, such as the long-term durability of concrete and its resistance to environmental conditions, could provide a more comprehensive assessment of its potential applications.

The strength of concrete is critical for the stability and safety of a structure, and its intended use is determined by various parameters, primarily mechanical performance [43]. In this study, different binder and aggregate combinations exhibited significant variations in early-age (7-day) compressive strength. Mix design not only ensures that concrete reaches its target strength level but also directly influences key factors such as workability, durability, and resistance to environmental conditions [44], [45].

According to the experimental results, the highest compressive strength was achieved in Mix 6. This mixture, containing 500 kg/m³ of cement and a 0.41 water/cement ratio, reached a compressive strength of 22.30 MPa at 7 days, outperforming all other mixes. The low water/cement ratio and balanced binder content supported the formation of a denser matrix, thereby enhancing early-age strength. Similar to findings by Dehghanpour et al. [46], where olivine filler promoted the formation of a robust calcium silicate hydrate (C-S-H) structure in cementitious mixtures, the denser matrix in Mix 6 likely benefited from such binding phases. This result suggests that Mix 6 could be a suitable candidate for prefabricated concrete elements requiring early strength, floor coverings, and structural elements that demand high load-bearing capacity.

On the other hand, the lowest strength value was observed in Mix 5. In this mixture, where the cement dosage was increased to 561 kg/m³ and the water/cement ratio was 0.41, the 7-day compressive strength dropped to 6.02 MPa. This suggests that excessive cement content may negatively affect the hydration process, leading to the formation of microcracks. Due to its low early-age strength, this mixture is not suitable for use in structural elements subjected to heavy loads. However, it could be considered for non-load-bearing applications, such as void filling or temporary site fillers, under specific conditions.

Mixtures with lower cement dosages, such as Mix 1, Mix 2, and Mix 3, exhibited limited mechanical performance in terms of their 7-day compressive strength. For example, Mix 1, containing 100% ferrochromium slag (9.16 MPa), Mix 2 with partial chromite powder (9.80 MPa), and Mix 3 (10.23 MPa) may be more suitable for applications such as filler concretes, walkable surfaces, or elements with low load-bearing capacity, where high early strength is not required.

These results highlight that in concrete design, not only the type of binder and aggregate but also the water/cement ratio, cement dosage, and the targeted early-age strength must be considered. Choosing an appropriate mix for the application area is crucial for producing sustainable and durable concrete, both in terms of mechanical and environmental performance.

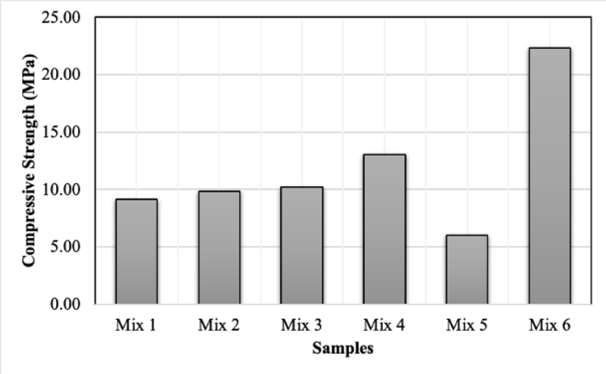

Figure 3. 7-day compressive strength values of the test samples

4. Conclusion

The use of industrial wastes in cement and concrete production is an important approach for reducing environmental pollution and lowering production costs. In this study, the effects of the partial replacement of cement with olivine mineral, along with the use of chromite powder as fine aggregate and ferrochromium slag as coarse aggregate in specific proportions, on concrete compressive strength were investigated. The following findings were obtained from the experiments, which reveal the effects of different binder and aggregate compositions on concrete strength:

- Mixtures with 5% olivine replacement for cement exhibited higher compressive strengths than the mixtures containing 100% cement. Specifically, Mix 3, which included 80% ferrochromium slag and 20% chromite powder, achieved a compressive strength of 10.23 MPa, indicating that olivine can enhance the strength of concrete.
- Increasing the cement dosage generally improves the compressive strength of concrete. Mix 6 (500 kg/m³ cement) achieved a compressive strength of 22.30 MPa. This result suggests that high cement dosages, up to a certain level, can significantly enhance the early-age strength of concrete.
- While reducing the water/cement ratio is generally a factor that increases strength, when the ratio falls below a certain threshold, hydration reactions may become limited, leading to potential strength losses.
- Among the mixtures with a 0.41 water/cement ratio, the mixture containing 500 kg/m³ of cement showed a compressive strength of 22.30 MPa, while the mixture with 561 kg/m³ of cement dropped to 6.02 MPa. This suggests that high cement dosages do not always result in higher strength and that the optimal water/cement ratio should be determined in balance with the binder content.

Conflict of Interest

The prepared article does not have any conflict of interest with any individual/institution.

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