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Strength and Performance of Polymer-modified Concrete with Waste Gabbro Aggregate under Freeze-Thaw Cycles

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ABSTRACT

Concrete is a widely used construction material; however, its performance can be significantly affected by the quality and characteristics of the aggregates used. In recent years, interest in utilizing recycled and waste materials has increased. The benefits of such materials include enhancing concrete properties and promoting sustainability. This paper presents an experimental study of the mechanical properties of polymer-modified concrete by utilizing waste gabbro as a coarse aggregate replacement. Styrene Butadiene Rubber (SBR) was used as a polymer modifier in the concrete mix at 10% of the cement weight, and the superplasticizer Flocrete PC200 was added at 1% of the cement weight. The study evaluates key mechanical properties, including compressive strength and tensile strength at 28, 60, and 90 days. Five replacement ratios of gabbro were tested: 0%, 25%, 50%,75%, and 100%. The effect of freeze-thaw cycles on concrete mixes was also examined. The findings indicate that substituting traditional aggregates with gabbro rock enhances the mechanical properties of the concrete and improves its residual strength after exposure to freeze-thaw cycles. Particularly, the compressive strength increased by up to 31.7% at 100% replacement ratio, while the tensile strength improved by 52% at the same ratio.

Keywords: Polymer-modified concrete, Gabbro, Compressive strength, Flexural strength, Absorption, Styrene butadiene rubber.

INTRODUCTION

Today, with the progress of innovation in the field of civil engineering, it has become vital to provide more economic and echo-friendly construction materials with enhanced mechanical properties. Concrete is considered as one of the most employed construction materials on the globe (Adam M. Neville, 2011; Neil Jackson, 1989). This can be attributed to its durability, versatility and cost effectiveness. With the growing concerns about resource depletion and environmental impacts, the use of recycled materials in concrete has become a significant focus of research (Kanagaraj, Lubloy, N. Anand, Viktor Hlavicka & Kiran, 2023). Aggregates, a major component of concrete, are divided into fine aggregate and coarse aggregate and typically occupy from 60% to 80% of the concrete volume. Several studies have highlighted the effect of including recycled aggregates, particularly recycled coarse aggregates (RCAs). The effect of using (RCAs) often results in reduced mechanical properties due to higher porosity and weaker interfacial transition zones (ITZs) compared to natural aggregates (Mathur, Joshi & Dave, 2023). However, polymer-modified concrete has shown the potential to mitigate these drawbacks by improving ITZ properties and reducing water absorption, leading to enhanced performance (Awchat, Kanhe & Rathore, 2011; Salami et al., 2024). Thus, the type of aggregate used can significantly affect the overall performance of concrete (Page & Page, M.M., 2007). This emphasizes the need for using more sustainable aggregates. In this study, gabbro rock was used as a partial or full replacement for coarse aggregate to enhance the polymer concrete properties. Gabbro, commonly called "black granite", is an igneous rock that can be found in the earth's crust and mantle. It has a variety of uses, such as curbing, paving stones, floor tiles, … etc. However, it is often used as an aggregate replacement when trying to attain higher compressive, flexural, and tensile strengths and abrasion resistance, because of its outstanding properties, which include its resistant to wear, heat, and weathering. Polymer concrete (PC), on the other hand, is a concrete type with polymers added as admixture. It is commonly used in precast and prestressed structural components, bridge decks, repair of old concrete, and other specialized fields. PC offers several advantages over traditional cement concrete, such as freeze-thaw durability, faster curing, higher compressive and flexural strengths and abrasion resistance, as well as improved adhesion, water tightness, and chemical resistance (Mindess, 2019; Salami et al., 2024). The use of PC in construction has become dominant in Europe and Japan since the 1970s and in the US during the 1980s (Mindess, 2019).

Several experimental programs have been conducted to study the mechanical properties of concrete using gabbro aggregate. However, most of these studies have focused on the effect of adding gabbro aggregate to ordinary concrete. An example of such research is the study conducted by Petrounias et al. (2018), which examined the effect of aggregate type on concrete strength. The physio-mechanical properties that influence the durability of concrete were also investigated. Six different types of aggregate were tested and categorized in three groups. Group II included gabbro, diabase, diorite and granodiorite. It was concluded that group II is suitable for concrete production. Rahal and Hassan (2021) studied the shear strength of plain concrete. Three types of coarse aggregate were tested, which included recycled low-strength waste concrete, limestone, and gabbro. The push-off shear strength, the cube compressive strength, and the shear failure surfaces were studied. It has been concluded that the recycled aggregate concrete has lower push-off shear and compressive strengths compared to the natural aggregates. Mahadeva (2019) experimentally investigated the strength properties of concrete using pre-owned gabbro. The study measured various parameters, including the flakiness index, elongation index, specific gravity, water absorption, and compressive strength of the concrete. The results indicated an improvement in the compressive strength of the concrete. Al-Fatlawy et al. (2018) studied the mechanical properties of concrete with waste gabbro aggregate replacement. The gabbro was sourced from local markets or buildings to reduce the overall cost of concrete. The results showed a significant increase in the mechanical properties of concrete when using gabbro compared with using normal aggregate concrete. The effect of using waste iron as fine aggregate and gabbro rocks as coarse aggregate on the mechanical properties of concrete was also investigated by Muwashee, Al Jabal & Al-Jameel (2020). Different replacement ratios of fine and coarse aggregates ranging from 0 to 100% were used. Their findings indicated that at a 75% replacement ratio, the compressive strength increased from 40.2 MPa to 51.8 MPa, while the flexural strength rose from 3.1 MPa to 8.9 MPa.

The effect of adding gabbro to high strength concrete was also examined by Atiş & Karahan (2008). Their research investigated the effect of aggregate type on the strength properties and abrasion resistance of high strength silica fume concrete. Five different aggregate types (gabbro, basalt, quartzite, limestone and sandstone) were used as a full replacement of coarse aggregate in the production of concrete. The results showed that the highest compressive strength and flexural tensile strength, as well as abrasion resistance, were achieved with gabbro concrete.

As mentioned before, most of the existing literature has focused on the effect of waste gabbro on ordinary concrete, whereas polymer concrete has not received adequate attention. Furthermore, there has been a limited exploration into the mechanical properties of polymer-modified concrete with gabbro aggregates, particularly under freeze-thaw cycles. Accordingly, this paper presents the results of an experimental investigation conducted to study and quantify the effect of adding waste gabbro rocks, sourced from buildings, as a partial or full replacement of coarse aggregate in polymer concrete. The mechanical properties of concrete, including absorption, compressive strength and tensile strength at different ages, were examined using five replacement ratios of gabbro. In addition, the effect of freeze-thaw cycles on concrete mixes was investigated.

MATERIALS AND EXPERIMENTAL PROCEDURE

Cement

Portland cement (Type V) was used in the concrete mixture for this study. Type-V cement is characterized by its high sulfate resistance, making it suitable for use in environments where the concrete is exposed to high sulfate concentrations, such as in soils or groundwater. The initial setting time of the cement was 94 minutes, and the final setting time was 285 minutes. Compressive strength of cement at 7 days was 25.2 MPa, as determined by a standard mortar test according to (Iraqi Standards Organization, 2019). Tables 1 and 2 show the chemical composition and the mineralogical composition of cement, respectively.

Table 1. Chemical composition of cement (%)

Chemical composition (wt.%)								
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	IR	LOI
19.4	4.9	4.8	61.3	2.2	2.2	0.1	0.3	3.7

Table 2. Mineralogical composition of cement (%)

Compound	Percentage by Weight (%)
C_3S (Tricalcium Silicate)	41.5
C_2S (Dicalcium Silicate)	38.4
C_3A (Tricalcium Aluminate)	3.7
C_4AF (Tetracalcium Aluminoferrite)	10.2

Polymer

Polymers are commonly used in concrete mixtures to enhance several properties, such as flexural strength, compressive strength, modulus of elasticity, and resistance against frost. These polymers act as microstructure modifiers of concrete, and hence they improve the overall durability and performance of concrete mixes. There are several types of polymer that can be used in concrete mixtures, such as acrylic polymers, polyvinyl acetate (PVA), and Styrene Butadiene Rubber (SBR). In this study, SBR, comprising 10% of cement weight, was selected as the polymer modifier, due to its several benefits, including enhanced flexibility, improved adhesion, superior resistance to freeze-thaw cycles, and improved bonding strength (Taha, Alalaf & Tarsha, 2024; Kim, 2020). These properties make SBR more effective than other polymers for enhancing specific performance characteristics examined in this study. The detailed properties of SBR are given in Table 3.

Super-plasticizer

Super-plasticizers are admixtures used in concrete mixtures due to their many advantages, including improved workability, faster finishing, delayed setting time, and increased strength. Furthermore, when added, the water-cement ratio of the concrete can be reduced without affecting the mixture's workability. In this study, Flocrete PC200 was used as a super-plasticizer, with 1% of the cement weight. The physical properties of PC200 are provided in Table 3.

Table 3. Physical properties of SBR and super-plasticizer PC200

	SBR	Super-plasticizer
Chemical composition	**CH-CH2-CH2-CH ---C6H6--- Chains**	**Poly-carboxylic polymers (-COOH)**
State	Liquid	Liquid
Color	White	Yellow
Density [gr/cm^3]	1	1.0
PH value	8.2	-
Tensile strength for solid state [MPa]	7-28	-
Freezing point	-	≈ -3°C

Gabbro

Gabbro stands out as a popular choice in construction industry. It is more eco-friendly and less polluting compared to other synthetic building materials. Gabbro is often used as coarse aggregate to provide higher compressive, flexural, and tensile strengths, as well as abrasion resistance. In addition, gabbro is widely available worldwide, easy to obtain and more cost-effective. In this study, a preowned waste gabbro aggregate was used in concrete mixes at different ratios: 0%, 25%, 50%, 75%, and 100%. The compressive and flexural strengths, absorption, and density values of gabbro and natural gravel are presented in Table 4. The used gabbro came in different sizes, so it was ground to a maximum aggregate size of 20 mm.

Table 4. Properties of gabbro and natural gravel

Properties	Density [gr/cm^3]	Absorption (%)	Flexural strength [MPa]	Compressive strength [MPa]
Gabbro	2.9	0.005	18.5	163
Natural Gravel	2.7	1.2	3.2	95

AGGREGATE TYPES AND GRADING

Aggregates are generally classified into coarse and fine categories. Aggregate sizes larger than 4.75 mm are considered as coarse aggregate, while sizes smaller than 4.75 mm are classified as fine aggregate. The coarse aggregate used in this study is limestone natural gravel sourced from quarries in Najaf city, Iraq with a maximum size of 20 mm. Gravel grading is presented in Table 5. The fine aggregate used in this study is sand conforming to zone II, according to Indian standards (Bureau of Indian Standards, 2016) and its grading is shown in Table 6. The fineness modulus of sand was calculated as 3.1. For better clarity, the sieve analysis curves for coarse and fine aggregates are presented in Figs. (1) and (2), respectively.

Table 5. Grading of coarse aggregates with standard limits

Sieve size [mm]	% Passed by weight		
	Natural gravel	Waste gabbro aggregate	20 mm max. size, IS
40	100	100	100
20	95.4	95.8	95 – 100
10	27.3	27.1	25 – 55
4.75	2.6	2.3	0 – 10

Table 6. Grading of fine aggregates with standard limits

Sieve size [mm, micron]	% Passed by weight	
	Ordinary sand	Grading zone II, IS
10 mm	100	100
4.75	93.6	90-100
2.36	77.4	75-100
1.18	61.7	55-90
600 micron	42.8	35-59
300 micron	9.7	8-30
150 micron	1.3	0-10

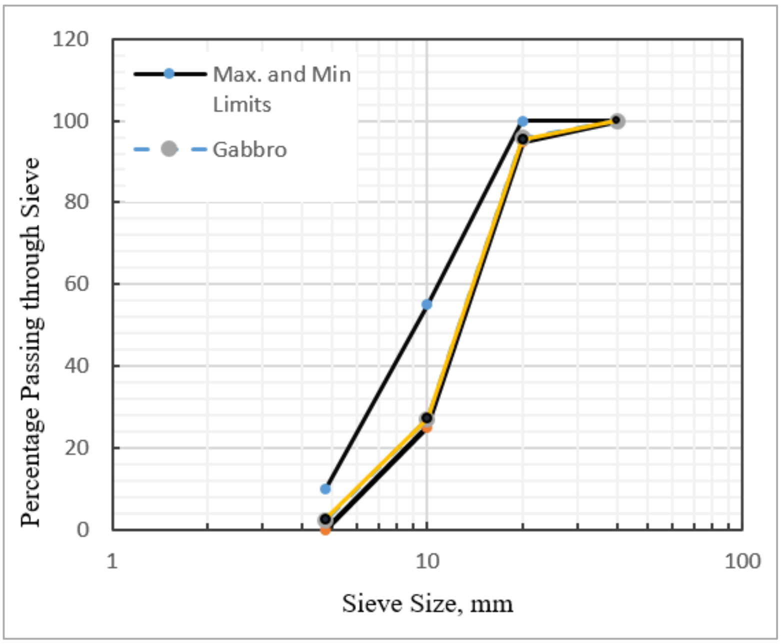

Figure (1): Sieve analysis curve of coarse aggregate

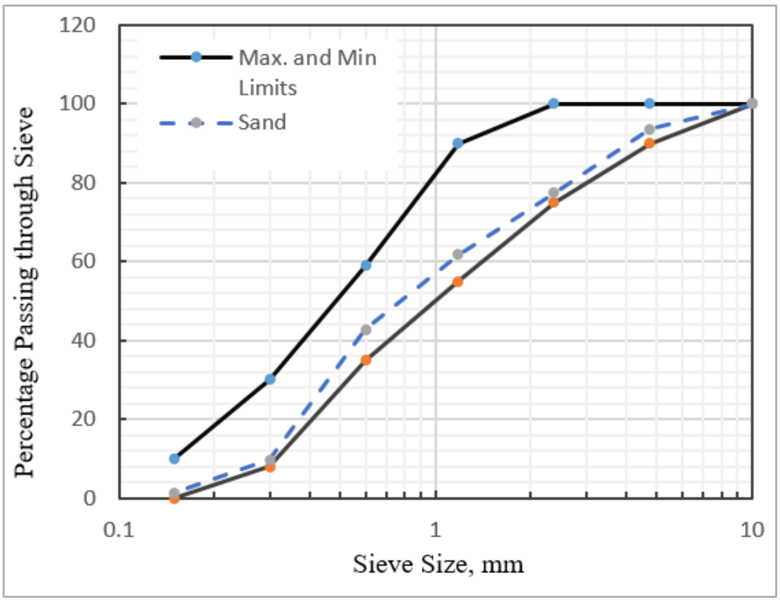

Figure (2): Sieve analysis curve of fine aggregate

MIXTURE COMPOSITION AND SAMPLE PREPARATION

A total of five concrete mixes were prepared for absorption, compressive and split tensile strength tests. The mix ratio of cement, fine aggregate, and coarse aggregate was 1:1:2 by mass. Gabbro aggregate was used in the concrete mixture as a replacement for coarse aggregate in five proportions: 0%, 25%, 50%, 75%, and 100%. A mid-range super-plasticizer, PC200, was added to the mixture to enhance workability. The amount used was 1% of cement weight.

For compressive-strength test, cubic steel molds with 100 mm sides were used to cast the concrete samples. Compressive and split tensile strength tests were carried out according to ((BSI), BS EN 12390-3, 2019), and ((BSI), BS EN, 12390-6, 2019), respectively. The concrete samples were cast using cylindrical molds with a diameter (d) of 100 mm and a length (L) of 200 mm. The value of the tensile strength F(t) was obtained using the following equation:

$$F(t) = \frac{2P}{\pi L d} \quad (1)$$

where P is the maximum applied load during the tensile test.

For each test, a total of nine samples were cast and tested at three different ages for all mixes. The test specimens were compacted using hand compaction, demolded after 48 hours, and then cured until the time of testing. The curing temperature was maintained at 21 ± 2 °C. Compressive and tensile strengths were tested at 28 days, 60 days, and 90 days. The strength measurements were evaluated using an ELE 2000 kN hydraulic press.

In the absorption test, three specimens were used for each mix. The specimens were initially dried in an oven at 95 °C for 24 hours. After this drying period, the specimens were left at room temperature for 3 hours before being submerged in distilled water for 24 hours. The average of the dried weight (w_1) and the saturated weight (w_2) was then measured. This procedure was conducted in accordance with ASTM C642-13 (ASTM, 2013). The absorption value was calculated using the following equation:

$$\%\, Absorption = \frac{w_2 - w_1}{w_1} \times 100. \quad (2)$$

The effect of freezing and thawing cycles on compressive strength was also assessed by using cubic concrete specimens with 100-mm sides. For each mix, nine specimens were tested, three of them at 28 days before freeze-thaw cycles (FTCs), while the remaining specimens were tested after exposure to FTCs at 15 and 30 days. Each FTC cycle (freeze-thaw cycle) consisted of thawing the specimens at 18 °C for 12 hours, followed by storing the specimens inside a freezer at −18 °C for 12 hours, according to (ASTM I., 2017). This cycle was repeated for 15 days and then, the specimens were tested for compressive strength to assess the deterioration in strength after FTCs. The remaining specimens were tested after 30 FTCs.

RESULTS AND DISCUSSION

Compressive Strength Test

The compressive strength of polymer concrete (PC) with varying replacement ratios of gabbro (0%, 25%, 50%, 75%, and 100%) and at different ages is shown in Table 7. To enhance visual representation, the measured compressive strengths are also illustrated in Figure (3). Based on the experimental results presented in Table 7, it can be observed that the compressive strength of concrete increases with the increase of gabbro replacement ratio. The maximum compressive strength is attained when the gabbro replacement ratio is 100%, indicating that a higher gabbro content positively influences the compressive strength of concrete. The ratio of increase in compressive strength at the age of 90 days ranges from 6.8% for a 25% replacement ratio to 31.7% for a 100% replacement ratio. This improvement in concrete compressive strength may be attributed to several key factors. First, the high density and strength of gabbro aggregate compared to other common aggregates, like sandstone or gravel, contribute to a stronger concrete matrix, thereby improving compressive strength. Another factor is the improved bonding with the cement paste. The rough texture and edges of gabbro enhance the mechanical interlocking with the cement paste, leading to better load transfer within the concrete, which results in greater resistance to compressive stresses. Finally, since gabbro has a lower porosity compared with other types of aggregate, as discussed in the following sub-section, it forms a stronger ITZ, which results in an improved compressive strength. Also, the enhanced bonding along with the low porosity of gabbro reduce the microcrack formation and propagation under compressive forces. Additionally, unlike the conventional types of recycled aggregate, which often contain microcracks or weaker materials, recycled gabbro retains its inherent physical and mechanical properties. These unique characteristics contribute significantly to the observed improvement in concrete strength.

Table 7. Compressive strength of concrete at different gabbro replacement ratios and curing times

Gabbro replacement ratio (%)	Compressive strength [MPa]			Strength increase (%)
	28 days	60 days	90 days	
0	30.6	33.7	34.4	-
25	34.9	36.1	36.7	6.8
50	36.7	38.8	39.2	13.9
75	39.1	41.8	42.9	24.8
100	41.2	44.5	45.3	31.7

Tensile Strength Test

The split tensile strength of PC with varied ratios of gabbro aggregate and at 28, 60, and 90 days is illustrated in Table 8. For enhanced comparison, the tensile strength measurements are also presented in Figure (4). As shown in Table 8 and Figure (4), the split tensile strength of concrete increases with the increase in gabbro aggregate ratio, similar to the trend in compressive strength. In addition, the ratio of increase of tensile strength ranges from 10.5% for a 25% gabbro replacement ratio to 52% for a 100% gabbro replacement ratio. This indicates that gabbro aggregate has a more pronounced effect on tensile strength compared to its effect on compressive strength. The reason for that can be attributed to several factors, such as the improved bonding between gabbro's rough edges and polymer cement paste. The enhanced interlocking leads to strengthen the internal structure, which is considered crucial to resist tensile stresses where cracks are more likely to form (Liu, Ren, Garcia-Troncoso, Mo & Ling, 2022; Özturan & Çeçen, 1997). Another reason is that concrete is naturally weaker in tension compared to compression, which could make tensile stresses more sensitive to aggregate properties and the enhanced concrete matrix provided by gabbro. Finally, since concrete is inherently strong in compression, this might cause that the compressive stress tends to reach a plateau at higher aggregate replacement ratios. Therefore, the relative effect of gabbro ratio on compressive stress is less compared to its effect on tensile stress.

Table 8. Tensile strength of concrete at different gabbro replacement ratios and curing times

Gabbro replacement ratio (%)	Tensile strength [MPa]			Strength increase (%)
	28 days	60 days	90 days	
0	2.8	3.1	3.2	-
25	2.9	3.4	3.6	10.5
50	3.4	4.2	4.2	29.9
75	4.1	4.6	4.8	46.5
100	4.6	4.9	4.9	52.0

Absorption Test

The absorption values of PC with varied gabbro replacement ratios at the age of 90 days are presented in Table 9. Based on the experimental results, and as expected, the absorption values decrease as the gabbro content increases. The reduction ratio rises from 3.2% for 25% gabbro content to 43.5% for full gabbro replacement. The results are also illustrated in Figure (5). The reduction in concrete absorption can be attributed to several factors, including the low porosity of gabbro. Gabbro is a dense, low porosity aggregate compared to other aggregate types, such as limestone or sandstone. When gabbro replaces a portion of aggregate, it decreases the overall porosity of concrete, thereby reducing water absorption. In addition, the rough structure of gabbro creates a strong interlocking mechanism (Hilal, 2021; Sun et al., 2024). This combination of reduced porosity and improved bonding helps minimize the development of micro-cracks during the curing process, resulting in lower water absorption.

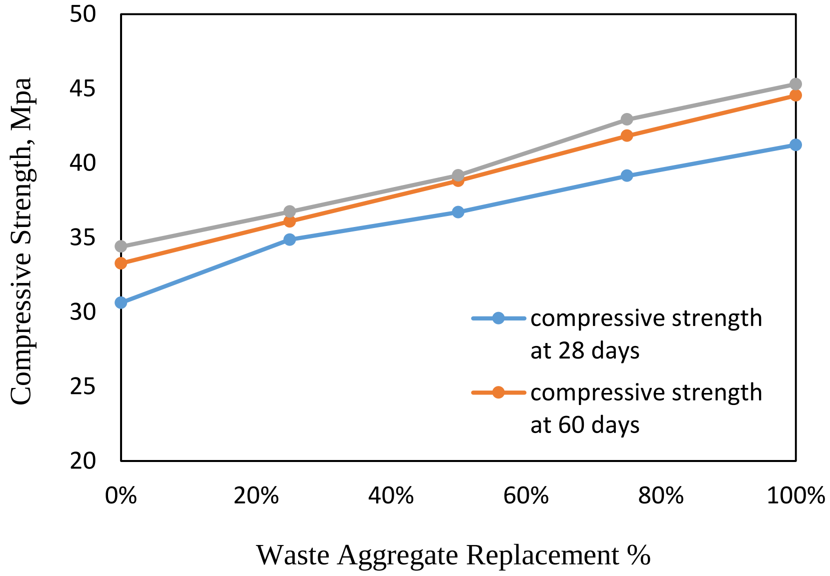

Figure (3): Compressive strength of concrete at Ages of 28, 60, and 90 days for varied values of gabbro replacement

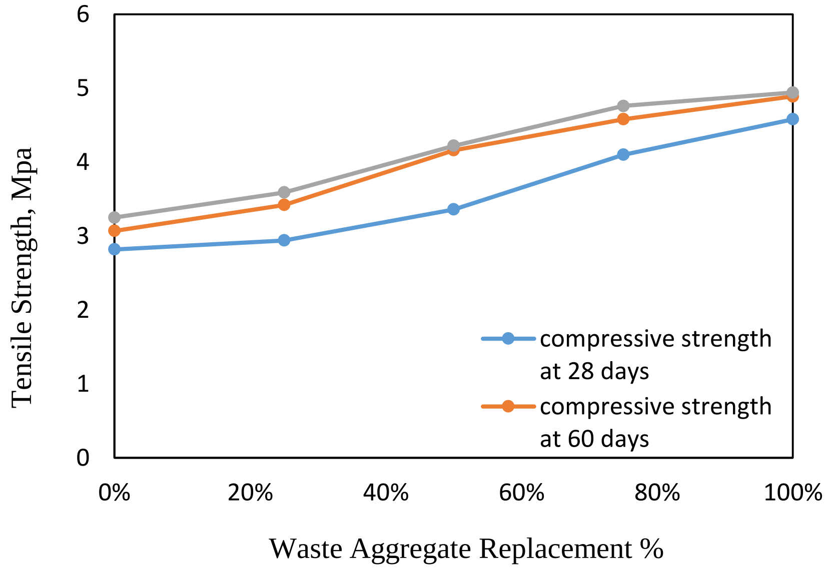

Figure (4): Tensile strength of concrete at ages of 28, 60, and 90 days for varied values of gabbro replacement

Table 9. Absorption of concrete at different gabbro replacement ratios at 90 days

Gabbro replacement ratio (%)	0	25	50	75	100
Absorption (%)	1.5	1.5	1.4	1.1	0.9
Absorption reduction (%)	-	3.2	12.3	27.3	43.5

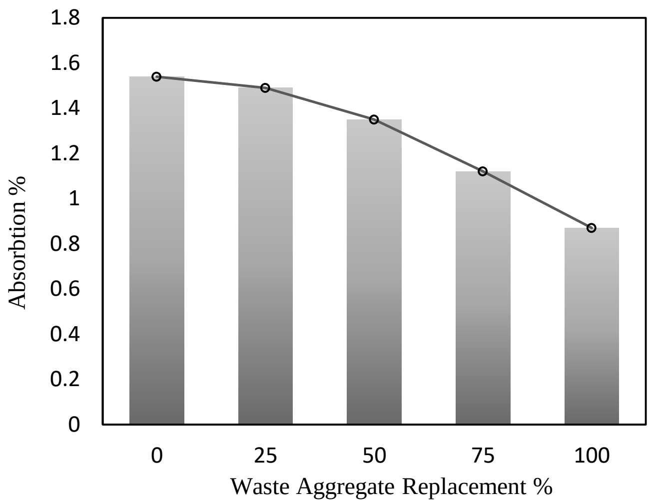

Figure (5): Absorption values of concrete at the age of 90 days for varied values of gabbro replacement

Freeze Thaw Cycle (FTC) Test

The experimental results of the FTC test, including the values of compressive strength after 15 and 30 FTCs for varied ratios of gabbro replacement are shown in Table 10. In addition, the percentage reduction in compressive strength of PC after 30 FTCs has been calculated and is also presented in the same table. For better illustration, the percentage reduction in compressive strength for varied gabbro contents is shown in Figure (6). As demonstrated by the experimental data, for 30 FTCs, the strength reduction is 18.6% for the reference mix, while it decreases significantly to 8.8% for full gabbro replacement. This indicates the positive effect of gabbro aggregate on improving the durability of PC. This is due to the nature of gabbro aggregate as a dense and durable material, which helps minimize the effects of FTCs by reducing the porosity of concrete and preventing extensive microcracking (Lamond & Pielert, 2006; Polat & Demirboga, 2010).

Table 10. Compressive strength of concrete at different gabbro replacement ratios and exposure to freeze-thaw cycles (FTCs)

Gabbro replacement ratio (%)	**Compressive strength without FTCs**	**Compressive strength after 15 FTCs**	**Compressive strength after 30 FTCs**	**Strength reduction (%)**
0	31.0	26.3	25.3	18.6%
25	35.2	30.9	29	17.6%
50	37.3	33.3	32.2	13.5%
75	39.5	36.0	35.6	9.9%
100	41.9	39.6	38.2	8.8%

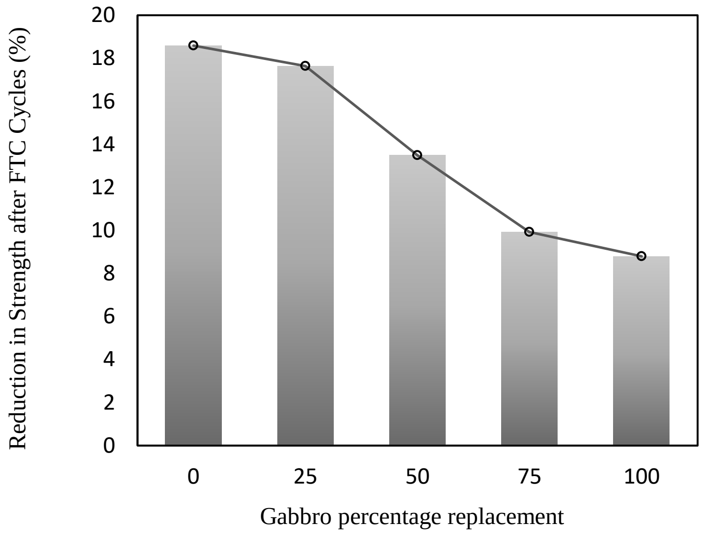

Figure (6): Reduction in compressive strength of concrete after 30 FTCs at the age of 90 days for varied values of gabbro replacement

CONCLUSIONS

An experimental program to study the effect of gabbro waste aggregate on the polymer- modified concrete (PC) was conducted. The study investigated the influence of different gabbro replacement ratios: 0%, 25%, 50%, 75%, and 100% on the mechanical properties of PC, including compressive strength and tensile strength, as well as absorption at 28, 60, and 90 days. The effect of freezing and thawing cycles on compressive strength was also assessed. The super-plasticizer and polymer modifier were used, at 1% and 10% of the cement weight, respectively. According to the experimental findings, it was observed that the mechanical properties of PC are significantly affected by the gabbro aggregate content. A noticeable improvement in the compressive strength and tensile strength values was observed with the increase of gabbro ratio, reaching a peak at 100% gabbro replacement ratio. Furthermore, it may be noted that the absorption values decrease as the gabbro content increases. Regarding the effect of gabbro content on freeze and thaw resistance, it was found that the strength reduction after 30 freeze-thaw cycles decreased with the increase of gabbro aggregate ratio. Accordingly, using a higher aggregate ratio in the polymer-concrete mix, typically between 75% and 100%, yields the optimum outcomes. However, other considerations, such as cost, workability, and availability should be taken into account. It is important to note certain constrains regarding the current study, such as environmental conditions. Critical environmental conditions, including chemical exposure and high-temperature resistance, were not assessed. Furthermore, the polymer concrete performance was evaluated at short periods (up to 90 days) and hence, long-term performance was not studied. Furthermore, the study mainly focused on the use of gabbro waste aggregate without exploring the combined effect of gabbro with other waste materials, such as fly ash or silica fume, to further enhance the performance of concrete. The effect of different types and percentages of polymer modifiers in combination with gabbro waste aggregate should be explored more. This could improve specific properties of the PC mix, such as crack resistance, chemical resistance, or durability under harsh environmental conditions.

Key Findings

- Substituting traditional aggregates with waste gabbro significantly enhanced the mechanical properties of polymer-modified concrete.
- Compressive strength increased by up to 31.7% and tensile strength improved by 52% at a 100% gabbro replacement ratio.
- Absorption decreased by 43.5% at full gabbro

replacement, enhancing water resistance.

- The inclusion of gabbro aggregate enhanced the residual strength of concrete after exposure to freeze-thaw cycles, with strength reductions decreasing from 18.6% for the reference mix to 8.8% for 100% gabbro replacement.

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