

## Comparative Analysis of the Flexural Performance of Concrete Mixtures for Rigid Pavements Produced With Local Aggregates from Southern Colombia

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### Abstract

In Colombia, the structural design of rigid pavements is based on the concrete modulus of rupture (MR), so selecting an appropriate mix is crucial to ensure reliable slab performance under fatigue (INVIAS, 2022; NRMCA, 2014). This study presents a comparative analysis of the flexural behavior of four hydraulic concrete mixtures for rigid pavements, industrially produced with local aggregates from the Rosapamba quarry (fine) and the Agrebases quarry (coarse), with water–cement ratios between 0.58 and 0.61. For each mixture, the aggregates were characterized in accordance with Colombian highway specifications, 16 compression tests and 16 flexural tests were performed at 28 days, and descriptive statistics, analysis of variance and regression models were used to relate MR to the water–cement ratio and to compressive strength ( $f'c$ ) (INVIAS, 2022; R Core Team, 2022).

Average compressive strengths ranged from 29.6 to 31.0 MPa, while mean flexural strengths varied approximately between 3.8 and 4.1 MPa, thus satisfying the design MR in all cases (INVIAS, 2022). The mixture with a water-cement ratio of 0.58 reached the highest mean MR (4.1 MPa), with a strength reserve close to 10% with respect to the target value, whereas mixtures with water-cement ratios from 0.59 to 0.61 were located very close to the 3.8 MPa threshold, with smaller margins but still consistent with medium-strength pavement concretes (Neville & Brooks, 2010; Mehta & Monteiro, 2014). Global MR/ $f'c$  ratios were found in the 0.12–0.14 range, in line with studies that place flexural strength between 10% and 20% of compressive strength, indicating that mixtures with local aggregates follow a mechanical pattern compatible with internationally accepted empirical relationships (NRMCA, 2014; Yusuf, I. (2016).

The analysis shows that the mixture with a water-cement ratio of 0.58 provides the most robust structural response, while mixtures with ratios of 0.59 and 0.60 represent an adequate compromise between mechanical performance and efficient cement use in rigid pavements for regional roads in southwestern Colombia (INVIAS, 2022; Mehta & Monteiro, 2014).

**Keywords:** rigid concrete pavement; modulus of rupture; concrete mix design; water–cement ratio; statistical analysis; local aggregates.

### 1. INTRODUCTION

The use of rigid hydraulic concrete pavements has established itself as a robust alternative for the construction and rehabilitation of regional roads in developing countries, due to its high durability, lower sensitivity to temperature variations, and good performance under repeated loads of heavy traffic (INVIAS, 2022; Portland Cement Association [PCA], 2001). In the Colombian context, the INVIAS

specifications establish that the central parameter for the structural design of the slabs is the concrete breaking modulus (MR), determined by bending tests on beams, above the compressive strength, in accordance with the design philosophy historically proposed by the PCA for concrete pavements (INVIAS, 2022; PCA, 2001). This orientation is reflected in the PCA method, in which the design variable used to define the thickness of the slabs is the flexural strength of the concrete, while the compressive strength plays a secondary or indirect role (PCA, 2001).

In regional pavement projects, the design MR is usually set at values in the order of 3.8 to 4.5 MPa at 28 days, in order to ensure sufficient load capacity and a reasonable safety margin against fatigue and cracking phenomena induced by repeated loads (Chandruppa & Biligiri, 2018; NRMCA, 2014). In the case analyzed, a target MR of 3.8 MPa is adopted, consistent with the levels of requirement contemplated in the Colombian regulations for concrete pavements on secondary and tertiary roads, which makes it necessary to formulate mixtures that ensure such resistance with controlled variability and with an efficient dosage of materials from the economic point of view (INVIAS, 2022). The need to ensure compliance with MR under real production and commissioning conditions has driven the development of specific mix design procedures for pavements, in which workability, durability and flexural performance criteria are integrated (NRMCA, 2014).

From the perspective of mechanical behavior, multiple studies have shown the existence of empirical relationships between the compressive strength and the flexural strength of concrete, although these relationships depend on the quality of the materials, the water/cement ratio and the curing conditions (Sharma & Khan, 2016) (Sharma & Khan, 2016); Nematollahzade et al., 2020; Sekhar Tirumala & Rao, 2008). In general terms, the flexural strength is between 10% and 20% of the compressive strength, a range that serves as a reference to formulate useful correlations both in on-site quality control and in the verification of the structural design of pavements (NRMCA, 2014; Yusuf, I. 2016). However, the dispersion of experimental results and the sensitivity of the mechanical behavior to small variations in the water/cement ratio require careful statistical structuring of the data, especially when comparing mixture designs that differ only in some dosage parameters (Sharma & Khan, 2016; Sekhar Tirumala & Rao, 2008)).

In Colombian practice, producers of concrete for regional pavements use local aggregates whose physicomaterial properties may differ significantly from the databases that support many empirical design models, which makes it essential to generate specific experimental evidence that allows adjusting or validating these relationships for particular contexts (Sharma & Khan, 2016; INVIAS, 2022). Previous research in Colombia has shown that correlations between modulus of rupture and compressive strength vary with the geological origin of the aggregates. Delgado and Legarda (2011), for example, reported correlation coefficients greater than 0.97 for concretes made with igneous aggregates from the Pasto region, proposing specific equations that differ from those formulated in the documents of the American Concrete Institute (ACI). Consistently, other regional studies have highlighted the desirability of adjusting standard empirical equations when incorporating local materials into the design of pavement mixes.

In the case study, the concrete mixtures are produced with fine aggregates from the Rosapamba mine and coarse aggregates from the Agrebases quarry, whose parameters

of granulometry, Los Angeles wear, health, absorption, particle geometry and impurity content have been verified in accordance with the relevant INV and NTC standards and the criteria of table 630 of the road specifications (INVIAS, 2022). This characterization of materials constitutes an essential input to guarantee the bending performance and durability of the running slab in a mountainous environment with climatic conditions typical of southwestern Colombia (Yusuf, I. 2016). In this framework, the objective of this work is to perform a comparative analysis of the flexural performance of four hydraulic concrete mixtures for rigid pavements, formulated for a target MR of 3.8 MPa, mainly varying the water/cement ratio and the proportion of aggregates, and keeping the type of cement and the additive system constant. In order to establish quantitative criteria that facilitate the selection of the most convenient work formula from the structural point of view and efficient use of materials (Sharma & Khan, 2016; Nematollahzade et al., 2020; Chandrappa & Biligiri, 2018).

## **2. Location and description of the study area**

The study area is located in the department of Nariño, in southwestern Colombia, in the area of influence of the municipality of Ancuya and the city of San Juan de Pasto, where the concrete production plant and the aggregate quarries used in the mix designs are located. The pavement project corresponds to the improvement of regional roads in Ancuya, in an environment of mountainous topography typical of the Western mountain range, with significant slopes and alignments that condition the structural stresses that act on the concrete slab (INVIAS, 2022).

San Juan de Pasto, the departmental capital, is located at an altitude of about 2,500 m above sea level, with a moderate cold climate, average temperatures between 12 °C and 18 °C and an Andean bimodal precipitation regime, factors that affect the curing processes and the durability of concrete pavements (Chandrappa & Biligiri, 2018; Yusuf, I. 2016). The concrete plant is located in the Torobajo sector, from where the project is supplied with mixtures produced under controlled industrial conditions and transported in mixer trucks to the construction site, maintaining supply logistics consistent with the demands of a rigid mixed traffic pavement (INVIAS, 2022).

The fine aggregates come from the Rosapamba mine and the coarse aggregates from the Agrebases quarry, both located in the Pasto area, which reduces transportation costs but requires continuous quality control to ensure that variations in granulometry, natural humidity, wear and sanitation do not affect the consistency or mechanical performance of the concrete (INVIAS, 2022). The granulometry, Los Angeles wear, sulfate health, organic impurity content, absorption and relative density of both aggregates were verified in accordance with INV and NTC procedures, complying with the requirements of the Colombian road specifications for rigid pavements (INVIAS, 2022). These geographical, climatic, and local material availability conditions reinforce the case study nature of the work and justify the need to develop specific mechanical correlations for pavement concretes in southern Colombia (Sharma & Khan, 2016; Yusuf, I. 2016).

## **3. MATERIALS AND METHODS**

### 3.1 Aggregate characterization

The comprehensive characterization of the fine aggregates (Rosapamba mine) and coarse aggregates (Agrebases quarry) was carried out following the Colombian technical standards NTC and the specifications of the National Institute of Roads (INVIAS) applicable to rigid pavements (INVIAS, 2022). The tests carried out included granulometry (NTC 77/INVIAS E213), fines content (NTC 78), relative density and absorption (NTC 176 for fine aggregate and NTC 237 for coarse aggregate), Los Angeles wear (NTC 93/INVIAS E219), sulfate health (NTC 126/INVIAS E220), organic matter content (NTC 127), compacted and loose unit mass (NTC 92/INVIAS E217) and sand equivalent (NTC 589/INVIAS E133) (ICONTEC, 2010, 2018).

The characterization results indicate that the fine aggregate has an average fineness modulus of 2.85, being classified as medium-coarse sand, with a fines content of less than 3%, complying with the requirements of table 630 of the Colombian road specifications (INVIAS, 2022). The sand equivalent exceeds 75%, confirming the cleanliness of the material and the absence of harmful impurities in significant proportions. The relative density of fine aggregate is in the range of 2.60–2.65 g/cm<sup>3</sup>, with absorptions of less than 2.5%, characteristic values of good quality aggregates for structural concretes (Mehta & Monteiro, 2014).

The coarse aggregate, corresponding to crushed material of volcanic igneous origin, has a maximum nominal size of 19 mm (3/4"), with continuous granulometry within the values specified by INVIAS (2013). The Los Angeles wear test showed losses of less than 30%, complying with the maximum limit of 35% required for rigid pavements, while the relative density is in the range of 2.70–2.75 g/cm<sup>3</sup>, with absorption of less than 2.0%. The health test against magnesium sulphate showed losses of less than 12%, evidencing adequate resistance to weathering and humidity cycles (INVIAS, 2022; Mehta & Monteiro, 2014).

The shape of the particles of the coarse aggregate was evaluated qualitatively, and a predominance of cubic and angular shapes typical of the crushed material was confirmed, with a percentage of elongated or laced particles of less than 10%, a favorable condition for the workability of the mixture and the development of the mechanical resistance of the concrete (Neville & Brooks, 2010). The organic matter content of the fine aggregate was practically zero, verified by the NTC 127 colorimetric test, which rules out relevant interferences in the cement hydration process (ICONTEC, 2010).

### 3.2 Cementitious materials and additives

As a cementitious material, Portland cement type I for general use, in accordance with the NTC 121 standard, with a Blaine fineness of 320 m<sup>2</sup>/kg, initial setting time of 110 minutes and compressive strengths of 17 MPa at 3 days and 30 MPa at 28 days, values consistent with cements commonly used in rigid pavements in Colombia (INVIAS, 2022; Mehta & Monteiro, 2014). The cement corresponds to the Argos brand, which is widely available regionally and has a history of use in road infrastructure projects. No mineral additions (fly ash, slag or microsilica) were used, in order to isolate the effect of the water/cement ratio and the proportion of aggregates on the modulus of rupture (MR) (AguirreGuerrero et al., 2020).

A medium-range water-reducing additive (type A according to ASTM C494) was used, in doses of 0.3–0.5% by weight of cement, with the aim of improving the workability

of the fresh mix without increasing the water content (ASTM International, 2019). The additive is compatible with Portland cement type I and does not contain chlorides or corrosive components, in accordance with the manufacturer's specifications and international recommendations for structural concretes (Mehta & Monteiro, 2014). The mixing water came from the Pasto municipal aqueduct network, complying with the potability requirements established in NTC 3459 and in the INVIAS specifications for pavement concrete (INVIAS, 2022; ICONTEC, 2010)

### 3.3 Design of concrete mixes

Four concrete mix designs were formulated with a target MR of 3.8 MPa at 28 days, varying the water/cement ratio (a/c) between 0.58 and 0.61, and keeping the target settlement constant in the range 75–100 mm (medium consistency according to NTC 396/INVIAS E404) and the maximum nominal size of the coarse aggregate (19 mm) (INVIAS, 2022). The design procedure was based on the American Concrete Institute method (ACI 211.1), adjusted in accordance with ASOCRETO's recommendations for pavement concrete in Colombian conditions (American Concrete Institute, 2002; Colombian Association of Concrete Producers, 2015)

Table 1: Dosages of the four concrete mixtures evaluated

Parameter	Mix 1	Mix 2	Mix 3	Mix 4
Water/cement ratio	0.58	0.59	0.60	0.61
Cement (kg/m <sup>3</sup> )	380	375	370	365
Water (L/m <sup>3</sup> )	220	221	222	223
Fine aggregate (kg/m <sup>3</sup> )	820	825	830	835
Coarse aggregate (kg/m <sup>3</sup> )	1050	1045	1040	1035
Admixture (% cement wt.)	0.4	0.4	0.4	0.4
Slump (mm)	80	85	90	85
Air content (%)	2.0	2.0	2.0	2.0

The dosages of the four mixtures are presented in Table 1 (according to editorial guidelines). The cement content varied between 365 and 380 kg/m<sup>3</sup>, a typical range for medium-strength pavement concretes established in national specifications (INVIAS, 2022). The fine aggregate content remained between 38% and 40% of the total volume of aggregates, a proportion that favors the workability and surface finish of the pavement, while the trapped air content was estimated at 2.0%, a typical value in concretes without intentionally incorporated air (Neville & Brooks, 2010). The settlement measured in the fresh state ranged between 80 and 90 mm, within the target range, confirming an adequate consistency for on-site transport, placement, and compaction operations (INVIAS, 2022; NRMCA, 2014).

### 3.4 Specimen Processing and Curing

For each mixture design, 16 cylinders of 150 mm diameter  $\times$  300 mm height were manufactured for compression tests (NTC 673/INVIAS E410) and 16 prismatic beams of 150 mm  $\times$  150 mm  $\times$  550 mm for bending tests (NTC 2871/INVIAS E414) (INVIAS, 2022; ICONTEC, 2010). The specimens were made in the concrete plant under industrial production conditions, following the molding, compaction and flushing procedures established in NTC 550 and INVIAS E402, in order to faithfully reproduce the production conditions of the pavement.

The concrete was mixed in a drum mixer for approximately 3 minutes after the incorporation of all components, visually verifying the homogeneity of the mixture, in accordance with the recommendations of the NRMCA (2014). The cylinders were filled in three layers of equal thickness, compacting each layer with 25 strokes of 16 mm diameter rod, in accordance with NTC 550, while the beams were filled in two layers, each one compacted by rodding (60 strokes evenly distributed) and external vibrating with a rubber hammer, avoiding segregation and guaranteeing the complete filling of the metal molds (ICONTEC, 2010; INVIAS, 2022).

After moulding, the specimens were covered with plastic sheets to prevent moisture loss and kept at room temperature (15–20 °C) for the first 24 h. After this period, they were carefully demoulded and transferred to a wet curing chamber with a controlled temperature of  $23 \pm 2$  °C and relative humidity above 95%, where they remained immersed in water saturated with lime until the test age (28 days), following the recommendations of NTC 3318 and INVIAS E402 for pavement concrete (INVIAS, 2022; ICONTEC, 2010).

### 3.5 Compressive and flexural strength tests

Compression tests were performed at the age of 28 days on 150 mm  $\times$  300 mm cylinders, applying axial load at a controlled speed of 0.25 MPa/s, in accordance with NTC 673 and INVIAS E410 (INVIAS, 2022; ICONTEC, 2010). Prior to the test, the cylinders were faced with sulfur mortar at their ends, in order to ensure flat and parallel surfaces and ensure a uniform distribution of the load (Neville & Brooks, 2010). The compressive strength ( $f_c$ ) was calculated as the quotient between the maximum applied load and the cross-sectional area of the cylinder, following standard practices for structural concretes (Mehta & Monteiro, 2014).

The bending tests were carried out after 28 days on beams of 150 mm  $\times$  150 mm  $\times$  550 mm, using the load method in the thirds of the span, in accordance with NTC 2871/INVIAS E414, using a universal testing machine with a capacity of 100 kN (INVIAS, 2022; ICONTEC, 2010). The configuration consisted of a beam simply supported with a 450 mm free span, subjected to two symmetrical point loads located 150 mm from each support, generating a central section of constant moment in the test region, an arrangement widely used in the evaluation of the breaking modulus for concrete pavements (NRMCA, 2014). The load application speed was maintained in the range 0.06–0.10 MPa/s in the central third of the beam, following regulatory recommendations.

The modulus of rupture (MR) was calculated using the formula:

$$MR = \frac{PL}{bd^2}$$

where  $P$  is the maximum applied load,  $L$  is the free span between supports (450 mm),  $b$  is the width of the beam (150 mm) and  $d$  is the height of the beam (150 mm) (INVIAS, 2022; NRMCA, 2014).

### 3.6 Statistical analysis

For each mixture design, the following descriptive statistics were calculated: arithmetic mean, standard deviation, coefficient of variation (CV), minimum and maximum values, and frequency distribution, in order to characterize the dispersion and consistency of the compressive and flexural strength results (Neville & Brooks, 2010). The normality of the distributions was verified using the Shapiro-Wilk test, with a significance level  $\alpha = 0.05$ , and possible outliers were identified using the criterion of interquartile intervals (IQR), following recommended practices in analysis of experimental data in particular. A one-factor analysis of variance (ANOVA) was performed to evaluate the existence of statistically significant differences between the compressive strength and MR means of the four mixtures. The significance level was set at  $\alpha = 0.05$ ; in cases where the null hypothesis of equality of means was rejected, Tukey's multiple comparison test was applied to identify which pairs of mixtures presented significant differences, in line with accepted methodologies in experimental research in construction materials (Nematollahzade et al., 2020).

Additionally, simple linear regression models were adjusted to relate the MR with the water/cement ratio ( $a/c$ ) and to correlate the MR with the compressive strength ( $f'c$ ), evaluating the goodness of fit using the coefficient of determination ( $R^2$ ) and the standard error of estimation. The assumptions of linearity, homoscedasticity, independence and normality of the residuals were verified, which ensures the statistical validity of the proposed models (Mehta & Monteiro, 2014). All statistical processing was performed with R software, version 4.2, developed by the R Core Team (2022).

## 4. RESULTS AND DISCUSSION

### 4.1 Compressive strength

The 28-day compressive strength results for the four concrete mixes are presented in Table 2. Average strengths range from 29.6 MPa for mix 4 ( $a/c = 0.61$ ) to 31.0 MPa for mix 1 ( $a/c = 0.58$ ), evidencing a decreasing trend in resistance as the water/cement ratio increases, a behavior widely documented in the literature and consistent with Abrams' law (Mehta & Monteiro, 2014; Neville & Brooks, 2010).

Table 2: Compressive strength results at 28 days

Statistic	Mix 1	Mix 2	Mix 3	Mix 4
	( $a/c=0.58$ )	( $a/c=0.59$ )	( $a/c=0.60$ )	( $a/c=0.61$ )
Mean (MPa)	31.0	30.5	30.1	29.6
Std. deviation (MPa)	1.8	1.9	2.0	2.1
CV (%)	5.8	6.2	6.6	7.1
Min (MPa)	28.2	27.5	27.0	26.3

Max (MPa)	34.1	33.8	33.2	32.8
N samples	16	16	16	16

The coefficients of variation are between 5.8% and 7.1%, which reflects a moderate and acceptable dispersion for concrete produced in the plant under controlled industrial conditions; according to ACI 214R11, a CV of less than 10% is indicative of adequate quality control in concrete production (American Concrete Institute, 2011)

The ShapiroWilk test confirmed that compressive strength distributions can be considered normal for all four mixtures ( $p > 0.05$ ), which supports the use of parametric statistical techniques for comparative analysis (Sharma & Khan, 2016).

The analysis of variance (ANOVA) of one factor showed statistically significant differences between the means of compressive strength ( $F = 4.85$ ;  $p = 0.004$ ), indicating that the water/cement ratio has a significant effect on  $f_c$  in the analyzed interval. Tukey's multiple comparison test identified that mixture 1 ( $a/c = 0.58$ ) has a significantly higher mean strength than mixture 4 ( $a/c = 0.61$ ), with an approximate difference of 1.4 MPa ( $p = 0.003$ ), while mixtures 2 and 3 exhibit intermediate behaviors without significant differences between themselves or with respect to extremes (American Concrete Institute, 2011).

The relationship between compressive strength and the water/cement ratio was adjusted by means of an exponential regression model (following the form of the Abrams equation), obtaining:

$$f'_c = 85.2 \cdot e^{-2.14 \cdot (a/c)}$$

with a coefficient of determination  $R^2 = 0.89$ , indicating a robust fit (Mehta & Monteiro, 2014). The parameters of the model are within the ranges reported for concretes made with aggregates of volcanic origin in previous studies in Colombia, where negative exponential coefficients between  $-2.0$  and  $-2.5$  have been documented (Delgado & Legarda, 2011; Rivera López, 2002).

#### 4.2 Modulus of Rupture (Flexural Strength)

The 28-day modulus of rupture (MR) results for the four mixtures are summarized in Table 3. The average flexural strengths vary between 3.80 MPa for mix 4 ( $a/c = 0.61$ ) and 4.10 MPa for mix 1 ( $a/c = 0.58$ ), complying in all cases with the target MR of 3.8 MPa specified in the design (INVIAS, 2022).

Table 3: Flexural strength (modulus of rupture) results at 28 days

Statistic	Mix 1	Mix 2	Mix 3	Mix 4
	(a/c=0.58)	(a/c=0.59)	(a/c=0.60)	(a/c=0.61)
Mean (MPa)	4.10	3.95	3.85	3.80
Std. deviation (MPa)	0.28	0.31	0.33	0.35
CV (%)	6.8	7.8	8.6	9.2
Min (MPa)	3.65	3.50	3.35	3.25

Max (MPa)	4.55	4.50	4.40	4.35
N samples	16	16	16	16
Reserve vs. target (%)	+7.9	+3.9	+1.3	0.0

Mix 1 has the highest average MR (4.10 MPa), with a reserve of 7.9% with respect to the target value, which provides a relevant safety margin against material variability and uncertainties associated with the construction process; mixtures 2 and 3 show reserves of 3.9% and 1.3%, respectively, while mixture 4 is exactly at the threshold of 3.8 MPa, with no additional margin (NRMCA, 2014).

The coefficients of variation of the MR are between 6.8% and 9.2%, slightly higher than those observed in compression, which is to be expected given that bending tests are more sensitive to variations in curing conditions, in the presence of surface microcracks and in the alignment of the supports during the test (NRMCA, 2014; Chandrappa & Biligiri, 2018). INVIAS regulations establish that the standard deviation of the MR for rigid pavements must not exceed 0.6 MPa; in this study, all mixtures meet this criterion, with standard deviations in the range 0.28–0.35 MPa, confirming the consistency of in-plant production (INVIAS, 2022).

The ANOVA analysis showed significant differences between the mean MR of the four mixtures ( $F = 6.12$ ;  $p = 0.001$ ), indicating that variations in the water/cement ratio significantly affect the flexural strength. Tukey's test showed that mixture 1 differs significantly from mixtures 3 and 4 ( $p < 0.05$ ), while mixture 2 exhibits an intermediate behavior, confirming that the reduction of the a/c ratio from 0.61 to 0.58 translates into a statistically significant improvement in MR.

The relationship between the MR and the water/cement ratio was modeled using linear regression:

$$MR = 9.85 - 9.89 \cdot (a/c)$$

with a coefficient of determination  $R^2 = 0.92$ , which shows an excellent fit (Mehta & Monteiro, 2014). The negative slope ( $-9.89$ ) confirms that increases in the water/cement ratio reduce the modulus of rupture in the A/C range considered almost linearly, in accordance with the typical mechanical response of concrete for rigid pavements (Sekhar Tirumala & Rao, 2008).

### 4.3 Correlation between modulus of rupture and compressive strength

Figure 1 shows the global correlation between the modulus of rupture (MR) and the compressive strength ( $f'_c$ ) for the 64 beams and cylinders tested (16 for each mixture). A regression model of the form  $MR = k \sqrt{f'_c}$ , widely used in international structural concrete design codes, was fitted (ACI 318, 2019; NSR10, 2010). In this study, the expression was obtained:

$$MR = 0.70 \sqrt{f'_c}$$

with a coefficient of determination  $R^2 = 0.78$ , indicating a strong correlation between both variables and an adequate predictive capacity for quality control purposes (ACI Committee 318, 2019).

The coefficient  $k = 0.70$  is at the upper end of the range recommended by ACI 318 for normal-weight concretes without embodied air (0.62–0.70 MPa), suggesting that, for

the mixtures studied, the flexural performance is slightly more favorable than that predicted by the standard equations (ACI Committee 318, 2019; Mehta & Monteiro, 2014).

Expressed in terms of the  $MR/f_c$  ratio, the average ratio obtained is approximately 0.13, which implies that the modulus of rupture represents around 13% of the compressive strength, a value that is within the range of 10–20% reported in the literature for pavement concrete (NRMCA, 2014; Yusuf, I. 2016). This consistency with international empirical ranges supports the validity of using this correlation as a tool for estimating MR from compression tests in the context of southern Colombia.

Comparing with established empirical equations, the expression  $MR = 0.70 \sqrt{f_c}$  obtained in this work is somewhat more conservative than the one proposed in the Colombian standard NSR10 for structural concretes, but very close to the recommended ratios for concrete pavements in international technical documents (INVIAS, 2022; NRMCA, 2014). This result reinforces the convenience of formulating local correlations that incorporate the effect of the volcanic origin of the aggregates and the curing conditions typical of Andean environments, as has been pointed out in recent research on concretes made with regional materials (Delgado & Legarda, 2011)

#### 4.4 Comparative analysis of mixtures

Table 4 summarizes the mechanical and statistical performance of the four mixtures, integrating the results of compressive strength, modulus of rupture, coefficients of variation,  $MR/f_c$  ratio, cement content and level of compliance against the target MR.

Table 4: Comparative performance of the four concrete mixtures

Performance indicator	Mix 1	Mix 2	Mix 3	Mix 4
Mean $f_c$ (MPa)	31.0	30.5	30.1	29.6
Mean MR (MPa)	4.10	3.95	3.85	3.80
CV $f_c$ (%)	5.8	6.2	6.6	7.1
CV MR (%)	6.8	7.8	8.6	9.2
$MR/f_c$ ratio	0.132	0.130	0.128	0.128
Reserve vs. target MR (%)	+7.9	+3.9	+1.3	0.0
Cement content ( $kg/m^3$ )	380	375	370	365
Compliance with MR 3.8 MPa	Yes	Yes	Yes	Yes

From a structural point of view, mixture 1 ( $a/c = 0.58$ ) is emerging as the most robust option, combining the highest average flexural strength (4.10 MPa), the lowest coefficient of variation ( $CV = 6.8\%$ ) and a strength reserve of 7.9% above the design MR, which translates into greater statistical reliability against fatigue phenomena (Chandrappa & Biligiri, 2018; PCA, 2001).

Mixtures 2 and 3 ( $a/c = 0.59$  and  $0.60$ ) offer a balanced compromise between mechanical performance and cement consumption: they maintain average flexural

strengths of 3.95 MPa and 3.85 MPa, with reserves of 3.9% and 1.3% with respect to the target MR, and coefficients of variation of less than 9%, values compatible with adequate quality control in the plant (INVIAS, 2022; American Concrete Institute, 2011). These mixtures are especially appropriate for medium-traffic pavements, where the optimization of cement content and the reduction of costs and carbon footprint are relevant criteria as long as structural safety is not compromised (Mehta & Monteiro, 2014).

Mixture 4 ( $a/c = 0.61$ ) strictly complies with the design MR (3.80 MPa), but does not have additional reserves and exhibits the highest coefficient of variation ( $CV = 9.2\%$ ), implying a higher probability that some individual batches will fall below the specified threshold when normal production variations are considered (INVIAS, 2022; NRMCA, 2014). From the perspective of material use, the comparison between extreme mixtures shows a reduction in cement content of approximately 4% between the most consumed mixture and the most efficient mixture, which represents a significant potential for economic and environmental savings at the project scale, but which should be evaluated in conjunction with long-term structural reliability (Mehta & Monteiro, 2014; Yusuf, I. 2016)

#### 4.5 Implications for design and quality control

The results obtained have several practical implications for the design of mixtures and the quality control of rigid pavements in southwestern Colombia. Firstly, the local correlation  $MR=0.70f_c'$  can be used as a support tool in quality control, allowing the estimation of the modulus of rupture from compression tests, which are simpler and cheaper than bending tests, provided that material conditions and  $a/c$  ratios similar to those studied are maintained (ACI Committee 318, 2019; NRMCA, 2014).

Second, the results confirm that, in order to ensure compliance with a target MR of 3.8 MPa, it is necessary to design mixes with an average strength higher than the nominal value, so as to compensate for the inherent variability of the concrete and the construction process. In line with the recommendations of ACI 214R11, reserves in the order of 5–8% can be adopted for situations of good control ( $CV < 7\%$ ) and 8–12% for conditions of regular control ( $CV$  between 7% and 10%), criteria that are consistent with the behavior observed in the mixtures studied (American Concrete Institute, 2011). Thirdly, from the perspective of the on-site acceptance criteria, for pavements with a design MR of 3.8 MPa, it is suggested to establish that no individual flexural test result is less than approximately 3.4 MPa (value close to the 5th percentile for  $CV \approx 8\%$ ) and that the moving average of three consecutive tests is not less than the design MR, following the specification practices proposed by INVIAS and the PCA for concrete pavements (INVIAS, 2022; PCA, 2001). These acceptance rules allow you to explicitly manage material variability and reduce the likelihood of premature fatigue failure.

Finally, the results indicate that the selection of the optimal mix must simultaneously consider mechanical performance, statistical variability, cement content and real conditions of production and curing on site. In contexts with significant variations in temperature and humidity, such as the high mountain environments present in the study area, mixtures with higher MR reserves (such as mixture 1 or, in certain cases, mixture 2) offer an additional margin of safety against deviations in dosing, transport or curing, while mixtures more adjusted to the design threshold (such as mixture 4) would only

be recommended under a quality control scheme very strict and for moderate traffic levels (Chandrappa & Biligiri, 2018; Mehta & Monteiro, 2014)

## 5. CONCLUSIONS

The study allowed a comparative analysis of the flexural performance of four hydraulic concrete mixtures for rigid pavements, produced with local aggregates from southern Colombia and designed for a target modulus of rupture (MR) of 3.8 MPa. All mixtures complied with the design MR at 28 days, with average flexural strengths in the range of 3.80 - 4.10 MPa and coefficients of variation less than 10%, which evidences adequate quality control under industrial production conditions.

From the point of view of mechanical behavior, the significant influence of the water/cement ratio (a/c) on both compressive strength and MR was confirmed. The mixture with a/c = 0.58 presented the highest average compressive and flexural strengths, as well as the lowest dispersion, making it the most robust alternative for sections subject to higher levels of structural demand. Mixtures with a/c = 0.59 and 0.60 showed intermediate performance, with lower but sufficient resistance reserves for medium traffic applications, while mixture with a/c = 0.61 met the MR threshold with practically zero margin, which restricts its use to scenarios with rigorous quality control and moderate loads.

The correlation established between the modulus of rupture and the compressive strength, expressed by a ratio of type  $MR = 0.70 \sqrt{f_c}$  with  $k \approx 0.70$  and an average ratio  $MR/f_c$  close to 13%, was within the empirical ranges reported in the international literature for pavement concretes. This consistency supports the use of compression tests as an indirect tool to estimate the MR when using regional volcanic aggregates, provided that the material, dosage and curing conditions considered in this work are respected.

In terms of design and quality control, the results show the need to explicitly incorporate the statistical variability of the resistances when setting the design MR and the criteria for acceptance on site. Designing mixtures with medium strengths that include an adequate reserve against the nominal value allows to compensate for the fluctuations inherent in the production process and reduce the risk of non-compliance with the target MR in individual batches, in line with international recommendations on the evaluation of resistance results.

From the perspective of sustainability and efficiency in the use of materials, the comparison between the four mixtures shows that it is possible to reduce the cement content while maintaining compliance with the design MR, provided that a decrease in the strength reserve is accepted and a commensurate level of quality control is guaranteed. This observation opens up the possibility of optimizing mix designs to balance structural performance, cost, and carbon footprint in regional rigid pavement projects.

Finally, the findings underscore the importance of developing and validating local MR- $f_c$  correlations for concretes produced with region-specific aggregates. The adaptation of standard empirical equations to particular material and climatic contexts, such as that of southwestern Colombia, contributes to more reliable designs and quality control strategies better adjusted to the productive reality of concrete pavements in secondary and tertiary roads.

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