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Evaluation of key aggregate parameters on the properties of ordinary and high strength concretes

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Abstract: This paper reports the results of a study conducted to determine the influence of coarse aggregate type on the workability, compressive strength, and flexural strength of normal and high strength concretes with target 28-day compressive strengths of 30 and 60 MPa and two water/cement ratios of 0.44 and 0.27. The concretes were prepared using four types of natural coarse aggregates, namely diabase, calcareous, river gravel, and basalt, with maximum particle sizes of 12.7 and 19.1 millimeters. Silica fume was added to the high-strength concretes at a replacement ratio to Portland cement of 10% by mass. The results showed that among all aggregates, basaltic aggregate with a maximum particle size of 12.7 millimeters produced concrete with the highest compressive and flexural strength, followed by limestone and river aggregate, indicating that particle size, surface texture, structure and mineralogical composition play a dominant role in the behavior of concretes, especially high strength concretes. Normal strength concretes showed similar compressive strengths, while the concrete containing limestone gave slightly higher strength. These results show that for a given water/cementitious material ratio, the influence of the type of coarse aggregate on the compressive strength of the concrete is more important for high strength concrete than for normal strength concrete.

Keywords: coarse aggregate types; compressive and tensile strengths; high strength concrete; silica fume.

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1. Introduction

Due to the critical shortage of natural resources, new sources of aggregates to produce concrete are being sought worldwide (Tam and Tam, 2007; Vince Beiser, 2019). The use of recycled materials could be an alternative to replace natural aggregates for concrete to meet at least part of the aggregate demand, as well as to reduce environmental problems and production costs. However, more information on the properties, cost-benefit and performance of concrete is still needed for the successful use of recycled aggregates (RA) (González-Fonteboa *et al.*, 2018; Mohammed, Sarsam and Hussien, 2018; Vinay Kumar, Ananthan and Balaji, 2018; Singh *et al.*, 2020). Literature reports have shown that recycled aggregates are typically of poor quality compared to natural aggregates (Yehia *et al.*, 2015). These technical problems include weak interfacial transition zones, porous and transverse cracking on demolished concrete, high sulphate and chloride contents, impurities, cement residues, poor grading, lower quality, and higher quality variability (Tam, Gao and Tam, 2006). The density, compressive strength, modulus of elasticity, flexural strength, tensile strength, splitting tensile strength, bond strength and can be greatly reduced and shrinkage increased (Tam and Tam, 2008). The prerequisite for the application of RA to high performance concrete is to overcome these weaknesses (Tam, Tam and Wang, 2007). Meanwhile, the evaluation of different sources of natural aggregates should continue, especially their influence on the properties of high strength concretes (HSC), since their properties, especially the strengths, are highly dependent on the properties of the aggregates, and natural aggregates have shown higher behavior when added to concrete mixes than recycled aggregates (Góra and Piasta, 2020).

Concrete technology has made great strides in the development of new and improved material performance (Fiorato, 1989; Beushausen and Dittmer, 2015). The remarkable increase in performance can be observed since 1970, when the chemical industry in Japan and Germany discovered and developed a new generation of chemical admixtures (high performance dispersants) (Mielenz Richard, 1984), based on complex organic molecules, whose incorporation into concrete allows a drastic reduction of the water of mixture and, consequently, a considerable increase in its strength and durability. These additives, also known as superplasticizers or high-efficiency water reducers, together with additional cementitious materials such as silica fume (SF), have opened up a new technological era in the world of concrete (Ullah *et al.*, 2022) making it possible to obtain very high-performance concretes with relative ease (Neville and Brooks J. J., 2010). The development and application of this type of high-strength concretes has increased significantly worldwide in the last decades, since they are used not only in large structures, such as offshore platforms and large bridges, but also in buildings, prefabricated elements, etc., where the possibility of reducing the amount of reinforcement and the dimensions of the elements has generated great benefits for the designers and constructors of the projects, although in cost overruns due to a higher quality control and a very demanding selection of materials, the benefits are even greater (Aonyas Serag and Nasear Hajer, 2022).

Since aggregates account for approximately three-quarters of the volume of concrete, aggregate properties have been shown to influence concrete quality (Wu *et al.*, 2001; Beshr, Almusallam and Maslehuddin, 2003; Meddah, Zitouni and Belâabes, 2010). Properties such as mechanical strength, elasticity, size, and surface texture of the aggregate particles, as well as the type and number of deleterious materials, have a direct effect (Mehta, Ezeldin and Aitcin, 1991; Beshr, Almusallam and Maslehuddin, 2003). The particle size and shape also have a direct effect on the strength of the concrete through the water requirement and workability of the mix (de Larrard and Belloc, 1992; Giaccio *et al.*, 1992). In HSC, there is a greater interaction between the cementitious matrix and the aggregate than in normal concretes due to the greater adhesion required between these constituents (Tasong, Lynsdale and Cripps, 1999). Thus, the behavior of HSCs is strongly influenced by the properties of the aggregate. Hence the importance of the type of aggregate used and its dosage per volume of concrete (Özturan and Çeçen, 1997).

The design of HSC mixes in terms of workability, strength development and durability need to be further optimized. This includes studies of the constituent materials, such as the type of cementitious agent to be used, the type of admixtures and their best use, the selection and processing of natural and artificial aggregates, among others. The influence of the different properties of aggregates, such as physical, chemical, and mineralogical properties on the behavior of concrete should be studied in more detail, especially for their use in special concretes (Parande, 2013; Srikanth *et al.*, 2022). Therefore, the present investigation was aimed at studying the influence of the type of aggregate, which is one of the many factors that significantly affect the behavior of HSC. Although a great deal of research has been carried out on this area, it is necessary to further explore this topic in many other areas to obtain optimal technical and economical applications for this material.

This paper presents a study that evaluates the influence of aggregate type on the workability, flexural and compressive strengths of conventional and HSC concretes with two water/cement ratios. In this study, four different types of aggregates with two maximum particle sizes, 12.7 and 19.1 millimeters, were used to determine the role of aggregates in the development of the mentioned concrete properties. The aggregates were characterized according to the standards established by ASTM and the British Standard (BS). In addition, Portland cement (PC), SF, superplasticizing admixture, natural rock and the mortars used in the mixes were characterized. The mixing, vibrating, placing, and curing methods were the conventional ones, duly specified in the standards. The particle size was adjusted to the distribution ranges recommended in the ASTM C 33 standard (ASTM International, 2018).

2. Materials and Methods

2.1 Cementitious Materials

Portland cement type V (PC), compatible with ASTM type I Portland cement (ASTM International, 2020a) without limestone powder, and commercial SF according to ASTM C 1240 (ASTM International, 2020b), were used as cementitious materials for the concrete mixes. The chemical and physical properties of PC and SF are shown in Table 1.

2.2 Aggregates

Coarse Aggregates

Four different sources of coarse natural aggregates were used in this study. A crushed diabase, crushed basalt, crushed calcareous, and river gravel were used to prepare the concrete mixtures. The coarse aggregates are defined as particles with two maximum particle sizes of 19 mm of 12.5 mm, selected to compare their influence on the mechanical properties of the concrete mixtures. The physical properties of the coarse aggregates selected for this study are shown in Table 2 and the distribution of their particle sizes in Figure 1. The aggregates were graded according to ASTM C33 (ASTM International, 2018) located in the middle of the standard grading ranges for their size designations.

Table 1 | Chemical composition and physical characteristics of PC and SF.

	PC	SF
Chemical Analyses, percent		
SiO_2 (%)	21.66	92
Al_2O_3 (%)	5.84	0.46
Fe_2O_3 (%)	4.28	4.57
CaO (%)	58.94	0.49
MgO (%)	1.40	0.68
Na_2O (%)	0.16	0.05
K_2O (%)	0.18	1.69
P_2O_5 (%)	—	0.06
TiO_2 (%)	—	0.02
SO_3 (%)	2.53	—
LOI	3.25	1.35
Physical tests		
Density (g/cm^3)	3.04	2.10
Fineness:		
Passing 45 µm, percent	98.0	99.0
Blaine specific surface, (m^2/Kg)	409	—
Specific surface, BET (m^2/Kg)	—	27,000
median grain size, µm	11	0.1
Color	Gray	Dark Gray
Pozzolanic Activity Index ASTM C618- ASTM C311	—	123

Compressive strength and Young's modulus of the aggregates were determined on rock cores drilled from the production sites. Table 2 and Figure 2 show these results and other physical properties of the coarse aggregates.

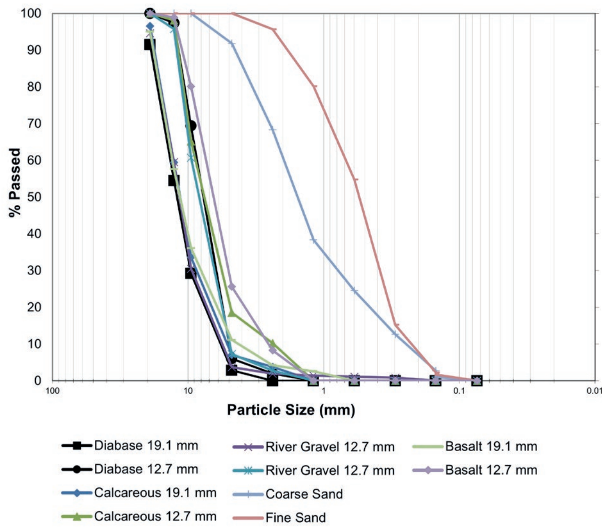

Figure 1 | Particle size distribution of coarse and fine aggregates.

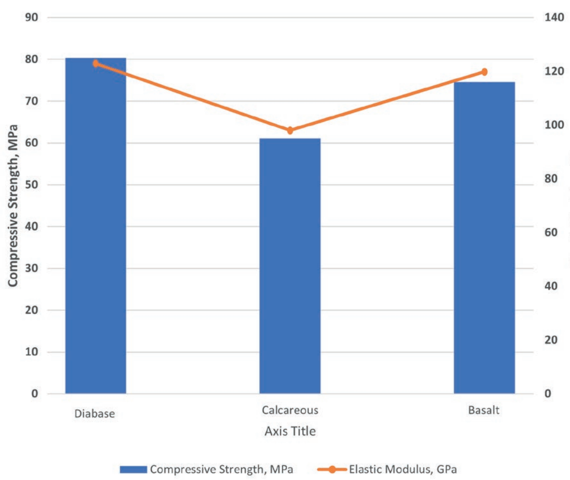

Figure 2 | Mechanical properties of core rock specimens.

Table 2 | Mechanical and physical properties of the coarse aggregates.

Type of Aggregate	Maximum particle sizes (mm)	Specific Gravity	Particle water absorption (%)	Bulk density (kg/m3)	Abrasion (%) (L.A. 500)	Compressive strength in core rock (MPa)	Elastic Modulus in core rock (Gpa)	Texture
Diabase	12.7/19.1	2.89	1.75	1700	11.14	125	79	Angular
Calcareous	12.7/19.1	2.83	1.48	1360	23	95	63	Angular
River Gravel	12.7/19.1	2.6	1.66	1420	19.5	-	-	Smooth
Basalt	12.7/19.1	2.93	1.53	1630	14.62	116	77	Angular

Fine Aggregates

Two river siliceous sands were used as fine aggregates: a coarse sand with a fineness modulus of 3.59, density of 2.85 g/cm^3 and absorption capacity of 1.52 and a fine sand with a fineness modulus of 2.52, density of 2.58 g/cm^3 and absorption capacity of 2.49. The aggregates were blended to produce a smooth gradation falling between the limits of ASTM C33 (ASTM International, 2018). The fine aggregates particle size distribution is shown in Figure 1.

2.3 Superplasticizer

A liquid polycarboxylate polymer superplasticizer (SP), conforming to ASTM C494 (ASTM International, 2019) was used as liquid chemical admixture. Municipal drinking water was used for all concrete mixes.

2.4 Mixture Proportions

Sixteen concrete mix designs were formulated and produced with two different water/cement ratios: 0.27 to produce HSC and 0.44 to produce conventional strength concretes. All HSC mixes included SF as a supplementary cementitious material (SCM), replacing PC at a rate of 10% by weight, to improve concrete microstructure and generate high strength. The mixes included eight high-strength mixes (M60) containing crushed diabase, crushed limestone, crushed basalt, and river gravel; of these six mixes, three contained the aforementioned aggregates with a maximum particle size of 19 millimeters and the three mixes contained aggregates with a maximum particle size of 12.5 millimeters. Additionally, eight control mixes (M30) were prepared without SF with the same maximum particle sizes as the previous mixes. The cementitious content of the high-strength mixes was 550 kg/m^3 and 340 kg/m^3 for the conventional strength mixes. Gravel and sand were mixed to adjust the gradation to the limits recommended by ASTM C33 (ASTM International, 2018) to produce workable and compact concrete mixes. The amount of each constituent used in the mixes is shown in Table 3.

The concrete mix codes shown in Table 3 consist of two parts: the first part indicates the type of aggregate: CD for crushed diabase, CCA for crushed limestone, CBA for crushed basalt and CGR for river gravel. The second part indicates the maximum aggregate size: NN for 19 millimeters and TW for 12.7 millimeters. This set of mixes allows us to evaluate the effect of the type and maximum size of the coarse aggregates on the selected mechanical properties of the concrete mixes. To keep the water/cement ratio constant, superplasticizer was used in different dosages, no air entraining admixtures were used.

2.5 Mixing and Casting Procedures

The concrete was mixed in a laboratory tilting drum mixer for a total of nine minutes. The mixing procedure followed ASTM C192 (ASTM International, 2019a). The coarse aggregate was added to the mixing pan with approximately one-third of the mix water. The aggregate was then mixed for approximately 30 seconds to saturate the aggregate. The mixing was then stopped, and the cementitious materials and fine aggregate were added to the pan. While mixing, the remaining water was slowly added. The final mix was mixed for 3 minutes, rested for 3 minutes, and mixed for a final 2 minutes. If superplasticizer was used, it was added slowly during the first 3 minutes of mixing. Immediately after mixing, a slump test was performed to measure the workability of each mix. 100 x 200 mm cylinders were cast from each mix for compressive strength (f'c), and 150 x 150 x 500 mm beams were cast for flexural strength (ft). The molds were oiled, poured in three layers, and compacted on a vibrating table to remove entrapped air. After casting, the concrete specimens were covered and stored under controlled temperature and humidity for 24 hours. The specimens were then demolded, marked, and placed in a curing room until the time of testing.

2.6 Testing of Concrete Samples

The mechanical performance of the hardened concrete was tested according to ASTM standards. Compressive strength was determined using 100 x 200 mm cylinders according to ASTM C39 [43] at 28 days for the conventional concretes and at 7, 14, 28, and 56 days of curing

Table 3 | Concrete mix designs in kg/m³.

Mix	Code	Type of aggregate	PC (kg/m³)	SF (kg/m³)	Water (kg/m³)	w/cm	Coarse Aggregate (kg/m³)	Coarse Sand (kg/m³)	Fine Sand (kg/m³)	SP (kg/m³)	Slump mm
M30	CDNN	Diabase 19.1 mm	440	-	197	0.44	861	714	469	1.7	74
	CDTW	Diabase 12.7 mm	440	-	197	0.44	839	713	489	1.8	76
	CCANN	Calcareous 19.1 mm	440	-	197	0.44	916	550	367	1.8	75
	CCATW	Calcareous 12.7 mm	440	-	197	0.44	817	563	436	1.7	77
	CRGNN	River Gravel 19.1 mm	440	-	197	0.44	985	540	420	1.7	75
	CRGTW	River Gravel 12.7 mm	440	-	197	0.44	803	663	487	1.8	75
	CBANN	Basalt 19.1 mm	440	-	197	0.44	1013	597	453	1.9	75
	CBATW	Basalt 12.7 mm	440	-	197	0.44	984	449	612	1.9	75
M60	CDNN	Diabase 19.1 mm	550	55	150	0.27	758	586	379	7.2	73
	CDTW	Diabase 12.7 mm	550	55	150	0.27	705	558	377	7.1	75
	CCANN	Calcareous 19.1 mm	550	55	150	0.27	833	500	333	7.3	75
	CCATW	Calcareous 12.7 mm	550	55	150	0.27	743	512	396	6.9	75
	CRGNN	River Gravel 19.1 mm	550	55	150	0.27	757	489	331	7	70
	CRGTW	River Gravel 12.7 mm	550	55	150	0.27	613	552	368	7.3	65
	CBANN	Basalt 19.1 mm	550	55	150	0.27	867	493	340	7.2	74
	CBATW	Basalt 12.7 mm	550	55	150	0.27	821	361	460	7.2	75

for the HSC, flexural strength expressed as Modulus of Rupture (MR) was determined by standard test method ASTM C 78 (third-point loading) using four beams per mix at 28 days of curing.

3 Results

3.1 Effect of Aggregates on conventional and High Strength Concrete Mixes

Workability

Figures 3 and 4 show the slump test results and superplasticizer requirements for the conventional and high-strength concrete mixes. As shown in Figure 3, the slump test results for all concrete mixes were found to be in the range of 70-75 millimeters, although there is a difference in the amount of superplasticizer used for the mixes, especially when comparing the high strength concrete mixes, which required a higher superplasticizer dosage to achieve the same slumps as the conventional concrete. This could be due to the presence of SF, which produces a higher water demand due to its high fineness. On the other hand, mixes with aggregates of rough texture and angular shape required a higher percentage of SP than mixes with smooth and rounded aggregates such as river gravel.

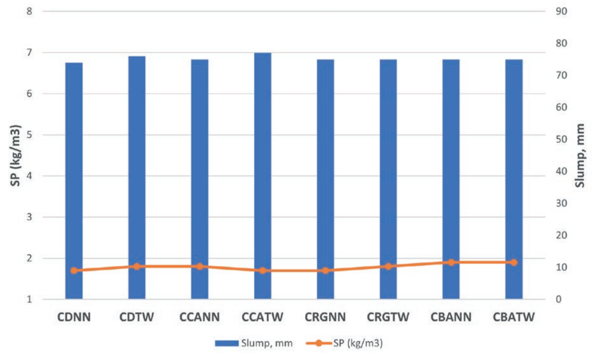

Figure 3 | Plasticizer required to maintain constant workability and variation in slump of conventional strength concrete mixes.

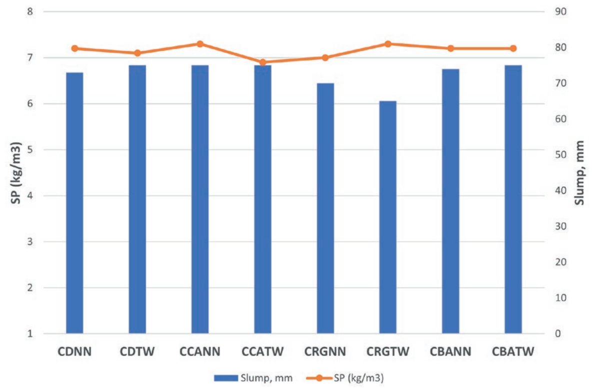

Figure 4 | Plasticizer required to maintain constant workability and variation in slump of high strength concrete mixes.

Compressive Strength

The results of the compressive strength tests after 28 days of curing are shown in Figure 5 for the conventional concretes with maximum aggregate sizes of 12.7 and 19 mm. The compressive strength of the high-strength concretes and the mortars corresponding to those concretes are shown in Figure 6.

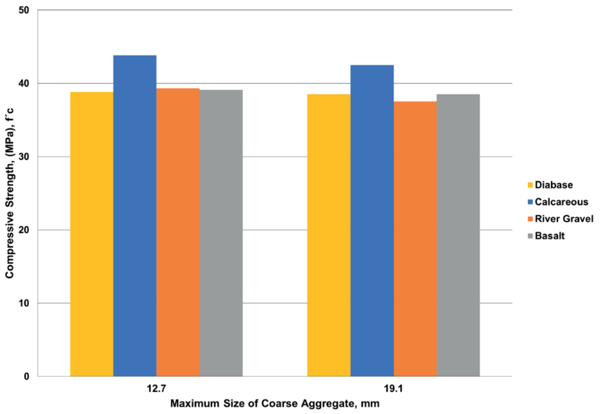

Figure 5 | Compressive strength of concrete with target strength of 30 MPa at 28 days.

Among all types of M30 concrete, the concrete with calcareous aggregate and 12.7 mm had the highest compressive strength than the rest of the mixes in the same group. However, the strength varies from one type of concrete to another only in the range of 1.9 to 7.5%, indicating that the type of aggregate does not have much effect on the compressive strength of normal strength concrete. This is because the aggregate is not the strength limiting factor as it is stronger than the cement matrix and the transition zone. In general, all aggregates have much higher strength than the cement matrix. Therefore, failure occurs only in the transition zone of normal concrete at ultimate loads (Wu *et al.*, 2001). Therefore, all the M30 mixes made with the three aggregates with their different maximum sizes showed very similar compressive strength.

In the case of mixes classified as M60, the compressive strength of the CBAMP mix was 6.4% and 10.9% higher than that of the CCAMP and CGRMP mixes, respectively, and 8.5%, 3.6% and 13.7% higher than that of the mixes containing 19 mm maximum size aggregates. This shows that the type of aggregate has a remarkable influence on the compressive strength of HSC and agrees with the results published in the literature (Wu *et al.*, 2001). Basalt is a rock that imparts a rough surface texture to the aggregate, which contributes to the mechanical strength of the concrete (Mehta, Ezeldin and Aitcin, 1991; Özturan and Çeçen, 1997; Wu *et al.*, 2001; Beshr, Almusallam and Maslehuddin, 2003). The rough texture and higher mechanical properties of the basalt aggregate caused the CBAMP mix to have a higher strength than other aggregates, followed by the mix with the same aggregate but with 19 mm maximum size. On the other hand, high-strength concretes are produced with relatively low w/cm ratios, in addition to mineral and chemical admixtures, therefore these concretes acquire a very dense and impermeable microstructure, making the cement matrix and the interfacial transition zone equal or close to the strength of the coarse aggregate. Therefore, aggregates can be considered as a limiting factor in strength, as they become susceptible to failure. In this regard, it becomes essential to select aggregates to produce high strength concrete (Wu *et al.*, 2001).

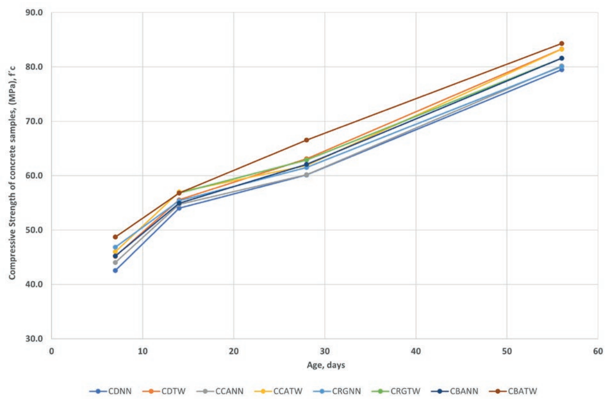

Figure 6 | Compressive strength of concrete with target strength of 60 MPa at different curing ages.

Calcareous aggregate also has a coarse texture, but the concrete made with it has a relatively lower compressive strength than the mixture with basalt. This must be due to the change in mineralogical composition and structure associated with these aggregates (Mehta, Ezeldin and Aitcin, 1991; Wu *et al.*, 2001; Beshr, Almusallam and Maslehuddin, 2003). Table 2 shows that the compressive strength of the core rock specimen corresponding to the calcareous aggregate is significantly lower than the basalt and diabase, which is an important factor in determining the strength of HSC. The CGRMP and CGRTC mixes with rounded aggregates showed relatively lower compressive strength than the other mixes, which is due to the smooth surface texture that reduces the bond between the cementitious matrix and the aggregate, weakening the transition zone (Giaccio *et al.*, 1992; Tasong, Lynsdale and Cripps, 1999).

As can be seen in Figures 5 and 6, the results showed that concrete mixes with 12 mm maximum aggregate size produced higher compressive strengths compared to concretes with 19.1 mm maximum aggregate size in normal and HSC at all ages. According to Zhao *et al.* (Zhao *et al.*, 2023), this can be attributed to the fact that the small-sized aggregates have a higher bonding strength with the matrix because they are intimately embedded in the mortar matrix, and because of the formation of a stronger and more homogeneous ITZ around the small aggregates, which restrains the cracking process and results in higher concrete strength.

Flexural Strength

Figure 7 shows the flexural strength of M60 concretes. The variations in the flexural strength of concretes made with different aggregates and maximum sizes are the same as the variations observed in the compressive strength. It is worth mentioning that the lowest flexural strength was presented for the mixes with smooth river aggregates, a situation that was already mentioned in the previous section, since the aggregate/paste adhesion is reduced, a situation that is more evident under loads that generate tension in the matrix, in which case a good adhesion between the constituents of the material is of vital importance.

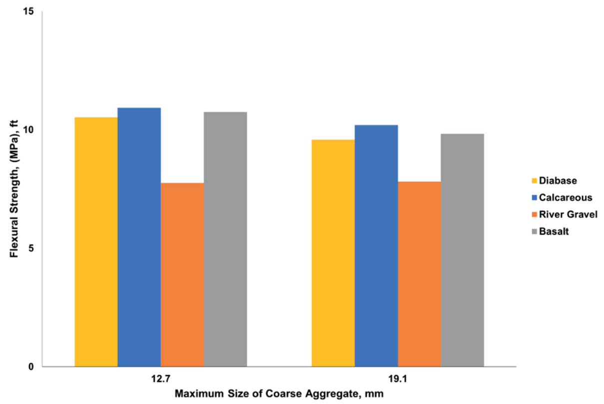

Figure 7 | Flexural strength of concrete with different types of aggregates and maximum sizes.

4. Conclusions

1. There is a direct relationship between aggregate compressive strength and the resulting concrete compressive and flexural strength where stronger aggregates control the overall strength of the concrete.

2. All the mixes, except for the CGRMP mix with river gravel TMA 12.5 millimeters, presented a slump greater than or equal to three inches. These values are within the range initially established for this parameter. Although, for normal concretes, this slump value defines a concrete as workable or of adequate placement, high strength concretes present a different behavior, due to their large amount of fines (cementitious material in large quantities per cubic meter of concrete), therefore, they become very dense, which makes their workability difficult.

3. The results of the compressive strength of the concrete specimens show the clear influence of the aggregate maximum sizes on the strengths. For all the mixtures, the strengths achieved with the maximum sizes of 12.5 millimeters exceeded those achieved with 19 millimeters. This behavior, described above, is of great importance for the design of high-strength concrete mixes. This is because, at larger sizes, the aggregate-paste transition zone becomes larger and in turn more heterogeneous, or also to the fact that the smaller maximum sizes present a lower percentage of cracks and internal grain defects from the blasting and crushing process of the rocks, making them more resistant to the blasting and crushing process.

4. As for the flexural strength, we can observe that the lowest strengths were observed for the rounded aggregate, this fact is because the flexural strength of the concrete is highly influenced by the shape and texture of the aggregates. In addition to the maximum size used, as well as the cleanliness of the aggregate surfaces, these factors directly influence the adherence of the aggregate to the concrete paste.

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