Reuse of Hydraulic Concrete Waste as a New Material in Construction Procedures: a Sustainable Alternative in Northwest Mexico

Reutilización de escombros de concreto hidráulico como nuevo material en procedimientos constructivos: una alternativa sustentable en el noroeste de méxico.

José Manuel Gutiérrez Moreno (Main Author)
Universidad Autónoma de Baja California, Ingeniería Civil, Facultad de Ingeniería.
manuel.gutierrez@uabc.edu.mx

Alejandro Mungaray Moctezuma
Universidad Autónoma de Baja California, Ingeniería Civil, Facultad de Ingeniería.
alejandro.mungaray@uabc.edu.mx

Michelle Hallack Alegría (Contact Author)
Universidad Autónoma de Baja California, Ingeniería Civil, Facultad de Ingeniería.
Blvd. Benito Juárez S/N, unidad universitaria C.P. 21280, Mexicali, Baja California, México.
+52686 5664270 Ext 1332
mhallack@uabc.edu.mx

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Abstract
Concrete demolition waste can be used as material for manufacturing high quality recycled coarse aggregates, which can replace natural aggregates to make hydraulic concrete mixes. In this study, the behavior of two hydraulic concrete mixes have been analyzed and tested under similar conditions. The comparison of natural concrete with 100% of natural aggregates, versus a specific recycled combination with 30% recycled coarse aggregate and 70% of natural coarse aggregate was studied. Results had shown a similar performance between the two concrete mixes after performing the mechanical tests in the laboratory. The incorporation of recycled aggregates in concrete allowed, in this case a competitive strength class one, which impact in reducing costs when applied in large concrete quantities. This alternative can represent a valuable environmental solution for construction and demolition waste disposal.

Keywords: Concrete Recycling, Recycled Aggregate, Debris, Environmental Solution.

Resumen
Los escombros de concreto hidráulico representan materia prima para la producción de agregados que pueden ser utilizados en la elaboración de nuevas mezclas de concreto hidráulico. En este trabajo, se estudia el comportamiento de dos tipos de mezclas de concreto hidráulico elaboradas y probadas bajo condiciones similares, en una comparativa entre concretos naturales con un 100% de agregados naturales, y concretos reciclados con 30% de agregados gruesos reciclados y 70% de agregados gruesos naturales. Se observa un desempeño similar entre ambas mezclas al someterse a pruebas mecánicas practicadas en laboratorio. Se concluye que la incorporación de agregados reciclados con estas características específicas, permite concretos de resistencia competitiva de clase uno, que reducen los costos en el uso de concreto masivo y representan una solución ambiental para la disposición final de los residuos de construcción y demolición.

Palabras Claves: Concreto Reciclado, Agregados Reciclados, Escombros, Solución Ambiental.

Introduction

The production and final disposal of construction and demolition waste represents an environmental problem with high costs and utilization of available space destined for disposal of municipal solid residues. In addition, large amounts of hydraulic concrete debris complicate the use of space in the truck for hauling and transportation and, in consequence, its disposal costs increases.

This study considers that concrete rubble can be crushed and used as coarse aggregate for manufacturing new concrete after proper cleaning of recycled aggregate which are usually superficially attached to fine particles. This research addresses the technical feasibility of using hydraulic concrete mixtures with 30% replacement of natural coarse aggregate by recycled coarse aggregates resulting from the crushing of rubble remnants of sidewalks and ready-mix concrete (new) with f'c = 250 kg/cm2.

It is important to notice that no such a studies have been previously executed in northwest Mexico, a seismic region with highly temperature extremes and semiarid climate which can affect concrete strength. Results for this experiment have shown a similar behavior in mixes of aggregates with and without replacement of recycled coarse material, mainly in the mechanical properties of concrete in hardened state, allowing a specific categorization as Class 1 for multiple uses.

Decreasing costs in civil engineering works represent an advantage when using recycled concrete for suitable purposes. Additionally, the incorporation of recycled aggregates have other benefits in the environmental field, such as reducing occupancy spaces for solid waste disposal and the possibility of contributing to a healthy environment by reducing 6% of the total use of materials, equivalent to 500 thousand tons per year, from virgin raw materials that end up returning to the environment as recycled concrete, The environmental benefit associated with reuse, recycling and conservation of materials that make up the concrete is a positive development, whose impacts are cumulative over time and space, because the consumption of sand, gravel and crushed rock are estimated in 1010 tons per year, for the annual production of 1.6 billion tons of concrete, representing approximately 7% of the global burden of carbon dioxide in the atmosphere (Hernandez and Mendoza, 2006).

This is possible when hydraulic concrete debris is recovered as recycled coarse aggregate for reuse in new construction procedures, whether it would be used in the construction of concrete base for road pavement or as part of hydraulic concrete mixes for other applications. This action can address the problem of transport and waste disposal of construction and demolition, particularly when these are separated and crushed on site where they are generated or settled.

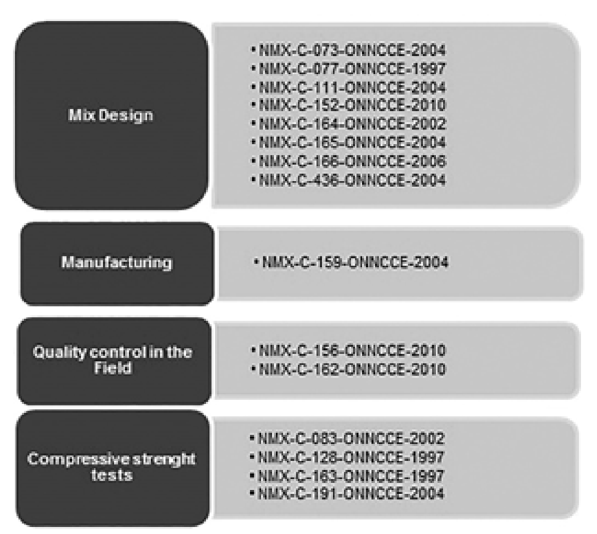
This allows a better use of spaces in load trucks, as well as the number of trips made to transport debris to the site where it would be processed and/or reused. Moreover, the contribution to reduction on emissions due to such a set of actions to incorporate the rubble in the new civil constructions, improve air quality (WBCSD, 2009).

Problem Description

Concrete waste is usually dumped in landfills and, it takes up a considerable volume that decreases the life of the landfill site or disposal. Also, debris can be found in illegal dumping sites, regularly in vacant lots or outside the urban area, which represents a starting point for pollution with debris and trash disposal in those places.

It can be a source of infection and hatcheries which is harmful for health. Indirectly, these actions decrease the visual quality of the landscape of any area. In this sense, Mexico is in a problematic debris management and has been classified by the General Act on integrated prevention and management of waste, Article 19, Section VII, where special handling of waste is addressed to reuse it into new construction procedures.

Diagram 1: Mexican ordinances applied in the four phases of the experiment. Original Source: Authors elaboration, 2015.



State of the Art

Knowing the properties of the materials that integrate hydraulic concrete mixes can deepen the understanding of their behavior during the construction and operation phases of the formed element. For instance, in some studies, recycled concrete has been characterized to determine its performance compared to traditional concrete (Rolón-Aguilar et al. 2007; Martinez et. al., 2006; Tabsh et. al., 2009; and Limbachiya, 2003).

Rolón-Aguilar et al. (2007) characterized concrete mixes with aggregates from pavement demolition. Results from that study shown compressive strength of 22MPa with cement consumption of 300 kg/m3, no additive mixes were used. Although, the concrete specimens with recycled aggregates were not compared to ones made with natural aggregates, the variation in compressive strength results was discussed getting the property of absorption the one showing results outside the permissible limits.

One more study (Martinez et. al., 2006) used recycled waste concrete mix for manufacturing of hydraulic concrete mixes and traditional concrete mixes prepared with cement consumption of 200, 300 and 400 kg/m3 and different water-cement material ratios. The comparison between natural and recycled concrete, resulted in that natural mixes are superior in compressive strength to the ones made with recycled concrete at 1.42%, 1.99% and 6.55%, respectively, for the cement consumption mentioned above. The authors stated that the recycled concrete mix found its best application in cement consumptions lower than 300 kg/cm3.

In a different work, two types of mixes were developed using debris demolition with 30MPa and 50MPa of strength, quarry (natural aggregates) and unknown sources (Tabsh et al., 2009). All mixes shared a maximum aggregate size of 19 mm and slump of 100 mm. Results showed that specimens of natural aggregate and recycled aggregate debris from 50MPa of strength were not showing a significant difference in compressive strength.

However, with the mixes made out from 30MPa concrete waste and unknown origin presented a decrease about 30% to 40% in compressive strength compared to the control mix (natural aggregates). The contribution of this study focused to demonstrate that the quality and strength of concrete debris impacts the quality and strength of the new concrete and the importance of sorting and separating the debris considering common features in order to reduce the variation among results of the same design.

In another study, it was mentioned that regarding the natural aggregate, recycled aggregates have a lower density range, varying from 4% to 8%, and a 2 to 6 times higher water absorption capacity (Limbachiya, 2003). However, it was stated that concrete resistance is not affected when using 30% replacement with recycled aggregate in a concrete mix. It is recommended limiting the recycled coarse aggregate content to 20% of the total coarse aggregate weight (EHE 2008). With this limitation, the final properties of recycled concrete are not that affected compared to a conventional concrete. Also, it is recommended limiting at 5% the recycled fine aggregate fraction in order to not affect concrete quality.

In an additional study, the physical, mechanical and durability concrete properties made with 25% and 100% of recycled aggregates using active and inert additions in these mixes were described, comparing them against traditional concrete pattern (Pavón et al. 2011). Regarding compressive strength, it was found that with 25% replacement of coarse aggregate without any additions equals the resistance attained by the natural concrete. While, concrete with 100% coarse aggregate replacement had a reduction in this property in the order of 12%.

Additionally, it was found that substitutions of 5% and 10% of silica fume instead cement, the mix with 25% replacement obtained 95% of the compressive strength of the natural concrete mix. In the case of the 100% recycled coarse aggregate mix, concrete properties results were lower than the natural concrete mix, which proves that the higher the amount of recycled aggregate, the lesser compressive strength attained, regardless of the additives used.

This highlights the good performance of concrete with 25% recycled aggregates and the significant improvements using active additives, which indicates the need to investigate recycled materials in concrete mixes to obtain comparable results to traditional concrete at a lower production cost.

Methodology

This research was done using natural limestone aggregates, hydraulic concrete waste made from natural limestone aggregates and previous resistance of f'c = 250 kg/cm2, Portland Cement strength class 40 and water reducing admixtures that meet ASTM C 494 standards.

In the case of recycled aggregates, it was manufactured by means of mechanical crushing jaws in a materials and concrete laboratory. The maximum size of aggregates delivered was 19 mm. The product was washed twice before starting the tests because of the quantity of fine particles attached to the material. After that, tests were started in order to characterize the produced material according to the established by the Mexican Official Standards (NOM).

The calculation of the properties of aggregates and concrete types were categorized into three stages: 1) materials characteristics; 2) fresh state concrete testing; and 3) hardened state concrete testing. Diagram 1 summarizes the main Mexican policy consulted to estimate these properties related to the quality of the concrete types manufactured in this study.

In this work, 132 cylindrical specimens that for acceptance testing were of 15x30 cm were taken to test their resistance to compressive axial stress. Each specimen was produced with water cement ratio of 0.5, cement consumption of 300 kg/m3 and natural sand in both types of mixes. Out of the total of samples, three specimens (6 cylinders) were tested at 7 days of age, and thirty samples (60 cylinders) at 28 days of age. Those specimens were made with 100% natural aggregates. Likewise, three assays were used for a 7-day test, and thirty samples for testing at 28 days. These samples were manufactured with 30% replacement of its total coarse aggregates for recycled aggregates.

Results

During the material characterization phase, the aggregates used for concrete manufacturing were subjected to the procedures indicated in the Mexican standards NMX-C-077-ONNCCE-1997 and, NMX-C-111-ONNCCE-2004, which consists on coarse and fine aggregates sieve analysis and aggregates properties.

The samples were homogenized to obtain the granulometry for both the coarse and fine aggregates. Results are shown in Table 1 for both types of samples, 70N.30R (70% natural coarse aggregate and 30% recycled coarse aggregate), and 100NAT (100% natural coarse aggregate).

The last two columns show the limits of coarse aggregate grain size according to the Mexican standard. In this sense, granulometry results showed a positive setting in the limits proposed by the regulations, for both types of samples. In addition, there are no significant differences between the two samples because the 70N.30R sample is compound of 70% natural coarse aggregate that is also the type included in the natural sample. It is important to note that the best adjustment was obtained from the 100NAT sample.

Moreover, it is necessary to get the characteristics of the materials to be used in the concrete mix design, so that the mix performance can be controlled when using it on site. Diagram 2 shows results for material properties found in laboratory. Testing was executed according to the methods established by the Mexican Standards corresponding to each case.

Table 1. Particle size of coarse aggregates. Original Source: Authors elaboration, 2015.

	70N.30R.	100 NAT.	NMX-C-111 / 2004	
Sieve Number	Percent Passing*	Percent Passing*	Min. (%)	Max. (%)
3”	100	100	100	100
2”	100	100	100	100
1 1/2 “	100	100	100	100
1”	100	100	100	100
3/4”	98.05	96.83	90	100
3/8”	53.32	53.54	20	55
4	29.59	28.92	0	10

*Percent passing=100-acumulative percent retained.

Table 2 shows sieve analysis for fine particles, sand in this case. The material passing sieve number 8 does not meet the minimum established in the Mexican standard by 4 percentage units. However, all other sizes were within the limits set by the regulations. Additional improvements include more fine particles and cement in the concrete mix to ensure best finishes. The combination of recycled and natural, coarse and fine materials used in the mix presented a well graded grain size. In this regard, it has been found that getting an appropriate particle size for the recycled aggregate produces good quality mixes, and a mechanical behavior similar to natural concrete (Martinez et al., 2006).

Table 2. Particle size of fine aggregates. Original Source: Authors elaboration 2015.

	NAT. SAND	NMX-C-111 / 2004	
Sieve Number	Percent Passing*	Min. (%)	Max. (%)
4	100	95	100
8	76	80	100
16	51	50	85
30	31	25	60
50	16	10	30
100	7	2	10

*Percent passing=100-acumulative percent retained.

Because of the high absorption obtained in the recycled materials, significant adjustments to the recycled mix were made. Consequently, water-reducing admixtures were included at a rate of 5 mL/kg without applying it to the fine fraction of the material recycled in this experiment because it showed a high absorption, with the possibility to have a negative effect on the concrete compressive strength. Recycled gravel typically reaches values in absorption up to 10%. In this case, the value obtained, approximately 5%, is about 10 times the natural coarse aggregate, and still is considered suitable for incorporation into new concrete mix (Kerkhoff and Siebel, 2001).

The Spanish Guide for Recycled Concrete (GEAR, 2012) establishes that the recycled samples analyzed resulted with an absorption average value around 7%, noting that sometimes these types of mixes can reach values up to 14% for this property. In this document is also based on the results of the properties of aggregates obtained from debris for implementation as granular material in slabs.

Density for coarse and fine aggregates was determined by the test method established in Mexican standards, as well as water absorption for coarse aggregates (NMX-C-164-ONNCCE-2002, NMX-C-165-ONNCCE-2004). Diagram 2 highlights a lower density value for recycled gravel which is a typical pattern for materials with mortar adhered to the gravel particles of old concrete.

While the rest of the values are equally acceptable with specific mass ranging between 2.4 and 2.9, so they were considered in concrete mixes design for proportioning applying the absolute volume method established by ACI 211.1. Also, the density of hydraulic cement strength class 40 used for concrete mixes manufacturing was estimated by applying the testing methods found in the Mexican standard (NMX-C-152-ONNCCE-2010), obtaining a value of 3.04.

Similarly, for estimating the compact density mass of the aggregates used in this experiment, the testing method established in the Mexican standard (NMX-C-073-ONNCCE-2004) was applied. This test is valid for fine and coarse aggregates, if their sizes do not exceed 150 mm. Density results are shown in Diagram 2, noting that recycled gravel is ranging in the typical values for these materials, 1200 to 1760 kg/m3 (Kosmatka et. al., 2004).

The volumetric coefficient calculation was performed using the procedure described in the Mexican standard (NMX-C-436-ONNCCE-2004). Both tested materials (natural and recycled gravel) were crashed in the laboratory. However, the sample with a fraction content of recycled material showed an increase in the shape factor, induced because the crashed rubble presented some angled and slightly elongated particles compared to the natural aggregate sample. It is important to mention that the combination of both types of aggregates can optimize the recycled concrete mix.

The dosage used in both natural sand samples, differed because one of them was replaced with 30% of its natural coarse aggregates by crushed rubble aggregates. As a result, when incorporated to the hydraulic concrete mixes generated in this research project, the product obtained is named as "recycled concrete mix".

The other type of sample analyzed, which was completely manufactured with natural aggregates, was called "reference or natural concrete mix". The dosage used for the mixes preparation was described in the Mexican standard (NMX-C-159-ONNCCE-2004) and following the recommendations published in the ACI-211.1.

The amounts used were; Water 157.87 kg/m3 on natual desing and 160.65 kg/m3 on recycled design, Cement 317.14 kg/m3 on natual desing and 304.00 kg/m3 on recycled design, Gravel 1096.20 kg/m3 on natual desing and 982.40 kg/m3 on recycled design, Sand 831.60 kg/m3 on natual desing and 831.60 kg/m3 on recycled design, the above is represented in Diagram 3 y Diagram 4, the dosage used for each type of sample mix is shown. The amount of admixture used was according to the recommendations made by the manufacturer.

The testing methods followed for concrete mixes in fresh state, were based on the procedures of the Mexican standards (NMX-C-156-ONNCCE-2010 and NMX-C-162-ONNCCE 2010). Table 3 presents results for concrete quality control that include slump, air content, and density tests for both newly prepared mixes.

Diagram 2: Properties of the aggregates. Original Source: Authors elaboration, 2015.

	Natural Gravel	Recycled Gravel	Natural Sand
Moisture (%)	0.91	2.00	6.00
Absorption (%)	0.53	5.82	6.30
Density	2.72	2.08	2.52
Volumetric Mass (kg/m^3)	1852	1704	1968
Volumetric Coefficient	0.20	0.22	-

Diagram 3. Mix natural concrete design. Original Source: Authors elaboration, 2015.

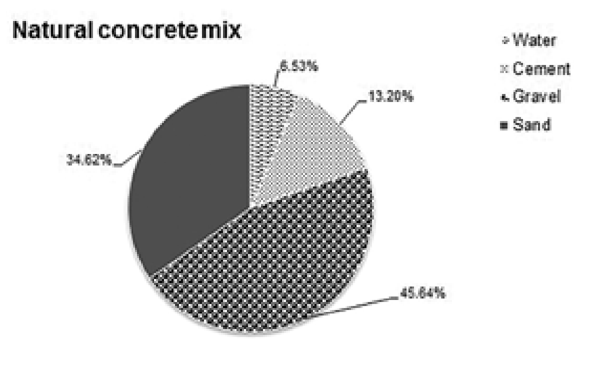
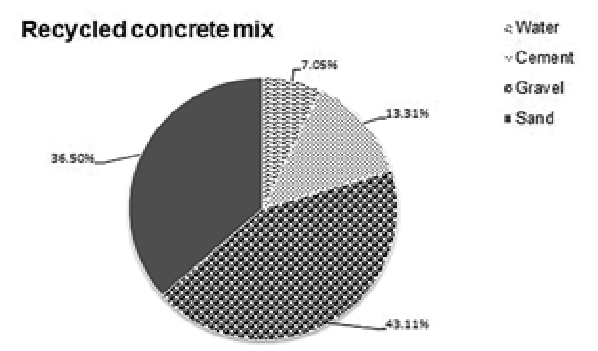


Diagram 4. Mix recycled concrete design. Original Source: Authors elaboration, 2015.



It can be observed that the average slump was greater in the natural mixture, although it is allowed increments of about 2.5 cm when using a tamping rod during the procedure (ASTM C143/C143M-12, 2012). In this case, the procedure was made manually, thus the slump of 10 cm is at its tolerance limit.

In the case of the recycled material mix design, quality control results met the preset requirements, even though the material had a slightly higher absorption percentage than 5%. The water-cement ratio was maintained in 0.5, and in consequence the expected concrete strength in hardened state was guaranteed. Regarding air content, results for both mixes were attained as expected taking the premise of "no air included".

The density of the mix design of natural concrete was higher; however, it is in the limits for normal-weight concrete. About the recycled concrete mix design, density was lower than the reference mix, recording 2282 kg/m3, placing it within the range for normal concrete weight. On the other hand, for concrete testing in hardened state, 6 cylinders of natural concrete, and 6 cylinders of recycled concrete were prepared for testing at 7 days of age.

Additionally, 60 cylinders of natural concrete, and 60 cylinders of recycled concrete were prepared for testing at 28 days of age, following the recommendations established by the ACI 318-14, Because there are no previous record of the behavior of concrete made with recycled aggregates locally (northwest Mexico), for comparison of the same properties and measurement of the standard deviation between these two types of mixing; natural and recycled, it is considered valid reducing the number of test specimens for future determinations related to the mix resistance.

On the subject of concrete testing in hardened state, the specimens prepared concrete were tested according to that described in the Mexican standard (NMX-C-083-ONNCCE-2002) to determine the compressive strength of concrete cylinders at 7 and 28 days of age. After concrete curing time was passed, the cylinders were taken out to record mass, diameter, and height, also to check if they were subject to correction by slenderness. It is noteworthy that in this research none required this procedure, because during the cylinder preparation standard molds of 30cm x 15cm were used (Figure 1).

Also, special care was taken to the molds were on a level, rigid surface, free of vibration. The top of the concrete cylinders were then struck off cleanly with the rod, and the cylinders were capped and marked. Subsequently, neoprene plates were placed in their optimal state (seamless) on both sides of the diameter of each cylinder, testing proceeded, and the average results of each specific group is summarized in Diagram 5.

At 7 days the hydraulic concrete reaches between 60% and 70% of the total strength that can achieve during its lifetime. The resistance of 70% is very similar to that recorded when the test is performed at 28 days of age, in the case of natural cylinders had already reached 60% of the average strength required in the reference mix design equal to 295 kg/cm2.

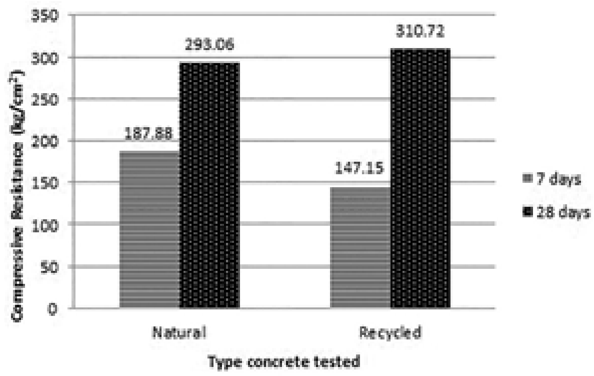
Recycled concrete cylinders reached just over 50% of the reference mix design strength. In this case, both types of concrete mixes shown no significant dispersion among the assays. About the specimens testing at 28 days, all met the expected strength of 210 kg/cm2, and some of them reached even higher values, 300 kg/cm2, which is the maximum value reached obtained with the recycled concrete cylinders.

Table 3. Results of quality control on concrete mixes in the field. Original Source: Authors elaboration, 2015.

Type of concrete	Natural	Recycled
Slump (cm)	12.5	7.2
Air content (%)	1.8	2.2
Density (kg/m3)	2401	2282

Figure 1: Concrete tested cylinders. Original Source: Authors elaboration, 2015.

Diagram 5. Compressive strength of concrete. Original Source: Authors elaboration, 2015.



However, the statistical analysis indicates that both samples tested were practically equivalent with an average mean difference of only 17 units in strength resistance. Additionally, recycled concrete cylinders obtained only an advantage of about 6% in strength than the natural concrete cylinders. These results have a confidence interval of 93.5% for natural specimens and 90.3% for the recycled ones, so the described behavior of the mixes is similar between the two groups.

It has been indicated that concrete replacement rates between 20% and 30% for recycled material do not affect the main properties of concrete; however, if you happen to have higher percentages, this properties may be impacted (Vidaud et.al. 2013). In another study, higher resistances of the order of 8.5% have been achieved for the recycled concrete with a water-cement ration of 0.68 (Dominguez et al., 2007). In this work, it was always maintained the same origin for concrete waste, the recycled fine particles were taken away, and the coarse fraction was double washed, cement consumes were in the order of 300 kg/cm3 (CPR 40 R), and a water/cement ration of 0.5.

Regarding the properties of tensile strength, modulus of rupture, and modulus of elasticity, the methods described in the Mexican standards (NMX-C-191-2004-ONNCCE, NMX-C-163-1997-ONNCCE and NMX-C-128-1997-ONNCCE) were not followed, because all cylinders were prepared for testing and determination of compressive strength, however were estimated from the formulas provided in the "Supplementary Technical Standards for design and construction of concrete structures of the Building Regulations of the Mexican Federal District" who stated that in the absence of experimental information those parameters can be estimated using the following formulas:

Tensile strength, particular class 1 (equal or greater than 25 MPa):

$$0.47\sqrt{f'c}, \quad in \quad Mpa \ (1.5\sqrt{f'c}, \quad in \frac{kg}{cm^2}) \qquad [1]$$

Modulus of rupture, concrete class 1 (equal or greater than 25 MPa):

$$0.63\sqrt{f'c}, \quad in \ Mpa \ (2\sqrt{f'c}, \quad in \ \frac{kg}{cm^2}) \qquad [2]$$

Modulus, concrete class 1 (equal or greater than 25 MPa):

$$4400\sqrt{f'c}, in \ Mpa \ (14000\sqrt{f'c}, \quad in \ \frac{kg}{cm^2}) \qquad [3]$$

The values obtained for these properties are presented in Table 4. It is important to note that the flexural strength required for hydraulic concrete pavement slabs ranges from 42 kg/cm2 to 48 kg/cm2, so any of the types of concrete produced are suitable for this use with the dosage arrangement made. However, it is recommended to increase the cement consumption used to over 400 kg/m3 for best results. On the other hand, results shown that with the mixes made can be used in other multiple applications.

Table 4. Estimated physical properties of concrete. Original Source: Authors elaboration, 2014.

Properties	Type of concrete	
	Natural	Recycled
Flexural Strength		
(kg/cm2)	34.18	35.19
Tensile Strength		
(kg/cm2)	25.64	26.39
Modulus of Elasticity (x103)		
(kg/cm2)	239	246

Conclusions

Results obtained in this investigation indicated that the recycled concrete mix design, which specifically include 30% replacement in their coarse aggregates, have a similar mechanical behavior than those with completely natural aggregates. Both mixes were sharing well-graded particle size, aggregate characteristics (except for absorption and density between both types of gravels); as well as water/cement ratio, and processing conditions of hydraulic concrete mixes.

The recycled concrete designed mix showed a favorable class one behavior, which according to laboratory tests have aptitude for applications, such as sidewalks, curbs, retaining walls, as well as in complementary pavement work. However, this replacement ration was not met the specifications for hydraulic concrete pavement slab construction. Thus, it is recommended to execute different replacement combinations, such as 10%-20%, under the same water/cement ratio can be circumstances that favor its use for paving slabs and other structural applications.

In this research it was found that recycled concrete setup and features had a good performance compared to its counterpart with 100% natural materials, with the possibility of multiple applications, including sidewalks and complementary pavement work. Likewise, it serves as a starting point for future research that may find percentages in which hydraulic concrete mixes using recycled material can be more competitive and having similar behaviors and even better than traditional concrete in structural applications.

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