

## **Characterization and Possible Uses of Recycled Aggregates from Construction and Demolition Waste from Mexico City**

Emiliano Moreno-Pérez<sup>a</sup>, \*Juan Hernández-Ávila<sup>a</sup>, Yamile Rangel-Martínez<sup>b</sup>,  
Eduardo Cerecedo-Sáenz<sup>a</sup>, Alberto Arenas-Flores<sup>a</sup>, Ma. Isabel Reyes-Valderrama<sup>a</sup>,  
Eleazar Salinas-Rodríguez<sup>a</sup>

<sup>(a)</sup>Área Académica de Ciencias de la Tierra y Materiales, Universidad Autónoma del Estado de Hidalgo, Carretera Pachuca-Tulancingo km. 4.5, Mineral de la Reforma, Hidalgo, México, Tel. (771) 7172000; ext. 2275 y 2276

<sup>(b)</sup>Área Académica de Ingeniería y Arquitectura, Universidad Autónoma del Estado de Hidalgo, Carretera Pachuca—Tulancingo km. 4.5, Mineral de la Reforma, Hidalgo, México  
Tel. (771) 7172000; ext. 4000

E mail: herjuan@uaeh.edu.mx

## Abstract

In this study, four samples of recycled aggregates from construction and demolition waste of Mexico City were characterized, in order to find innovative uses for this type of materials. Gravel and sand from a recycling plant were analyzed, as well as recycled aggregates in the laboratory from demolished concrete collected in landfills. The characterization was carried out by means of XRD, chemical microanalysis (EDS), pH measurement and sieve analysis.

The results reveal that the minerals present in the analyzed materials are triclinic feldspars, cristobalite and pyroxene which correspond to the natural aggregates, as well as variable amounts of calcite, product of the carbonation of the cement paste adhered to these aggregates and in a smaller proportion calcium hemicarboaluminate, rosenhanite and tobermorite. It was determined that the quality (amount of cement) of the original concrete that was recycled, has great influence on the granulometry and the chemical-mineralogical composition of the aggregates, since there will be different quantities and qualities of cement paste adhered to the aggregates of according to size. Finally the pH values measured in all samples fluctuate between 10.15 and 12.08, therefore it is suggested that these materials can be used in soil stabilization.

**Keywords:** recycled aggregates, cement paste, carbonation, calcite, pH

## 1. INTRODUCTION

According to the Mexico City NADF-007-RNAT-2013 [1] environmental norm, the amount of construction and demolition waste (CDW) generated by the city is of approximately 7,000 tons / day; 25% of such waste consist of demolished concrete that is usually disposed of in clandestine landfills, despite that the norm recommends recycling this material through a process involving selection, crushing, sieving, and storage, in order to reuse it as recycled aggregates in the construction cycle.

Numerous definitions have been suggested for these recycled materials. This study used the definition proposed by Zhao et al. [2], who define the recycled concrete aggregates as an intimate mix between the original natural aggregates (gravel and sand) and hardened cement paste adhered to them.

The environmental benefits of the use of recycled aggregates can play a key role in reducing the need for landfill waste disposal and conserve natural aggregates with benefits to the natural environment [3]. In that sense, particularly for Mexico City, Rivera-Mera [4] characterized recycled aggregates of the Concretos Reciclados SA plant from the physical point of view, considering the regulations for roads established by the IMT Mexican Transportation Institute, determining that these aggregates comply with said normativity, however to this day there is no mineralogical and chemical study available that could be used as a parameter to decide whether to use the recycled aggregates in geotechnical applications, such as sub-bases, bases, embankments, fillings etc. , in the manufacture of concrete or in other applications.

In accordance with the above, the objective of this work is to know the mineralogy and the chemical composition of 4 samples of recycled aggregates of demolished concrete in Mexico City, in order to find innovative uses for this recycled material. Sand and gravel were analyzed from “Concretos Reciclados S.A.”, a concrete recycling plant located in Iztapalapa (Mexico

City), and sand and gravel recycled in the laboratory (crushed and sieved) using demolished concrete collected at clandestine landfills located in the north of the City.

## **2. EXPERIMENTAL PROCEDURE**

### **2.1 Materials**

Plant-recycled aggregates were obtained by sampling materials directly from the processed piles (1/4"-grain to fine grain sand and 1" gravel) formed by the McCloskey movable recycling unit, model I44R at the Concretos Reciclados plant (figure 1a); on the other hand, laboratory-recycled aggregates were obtained by crushing and sieving demolished concrete collected at two clandestine landfills (empty lots) located in the north of Mexico City (figure 1b). Table 1 shows the sample quantities that were used in this study.

To produce the laboratory-recycled aggregates, fragments of demolished concrete collected in landfills were processed using a laboratory jaw crusher (Allis Mineral System), and manually classified using #4 mesh ASTM (4.75 mm) in order to separate gravel from sand.

In order to obtain adequate samples of the size required for the tests, the aforementioned recycled aggregates (gravel and sand) were homogenized and quartered manually per the NMX C-170-ONNCCE-1997 norm [5] (this norm does not coincide with any international standard), which provides specifications for the reduction of aggregate samples obtained in the field to the size required for tests.



**Figure 1.** (a) Mounds of recycled gravel at the Concretos Reciclados S.A. plant; (b) a landfill containing CDW where demolished concrete was collected.

**Table 1.**  
**Recycled concrete samples obtained in Mexico City**

Concretos Reciclados S.A. recycling plant		Concrete from landfills	
Plant-recycled gravel	Plant-recycled sand	Laboratory-recycled gravel	Laboratory-recycled sand
109.16 Kg	126.37 Kg	55.24 Kg	125.59 Kg

## 2.2 Methods

**2.2.1 Granulometric characterization.** To determine the size of recycled gravel and sands, samples of 10 kg for coarse aggregates and 1 kg for fine aggregates [6], were dried to constant weight prior to sieving. The size distribution was analyzed in accordance with NMX C-077-ONNCCE-1997 norm [7] (EN 933-1:1997), which describes sieve analyses and test methods for concrete aggregates.

**2.2.2 Chemical and mineralogical characterization.** These analyses were carried out using representative samples of recycled sand and gravel (plant and laboratory), which were ground until 100% of the sample passed through the # 200 ASTM ( $<75\mu$ ) mesh and dried at 100 ° C for 6 hours in a laboratory oven with digital controller.

The mineralogical composition was determined by X-ray diffraction (XRD), using an Equinox 2000 diffractometer (INEL) with CoK $\alpha$ 1 radiation. Phase identification was based on the COD Inorganics 2015 and Cements 2014 databases included in the Crystallography Open Database; Match! software was used in this procedure. V.1.10.

Element chemical composition was determined by energy-dispersive X-ray microanalysis (EDS) using a JEOL scanning electron microscope, model JSM-6300, and a NORAN X-ray detector, using an acceleration voltage of 30 Kv and a scanning area of 1.5 mm<sup>2</sup>. In order to obtain a representative analysis of these materials, the dry powders of the samples were placed on specimen stub in uniform layers; quantitative routines were performed using ZAF correction without standards.

To complement the results of the chemical microanalysis, pH measurements were made at room temperature with OAKTON 700 series pH meter equipped with an OAKTON electrode. For this purpose, 10 g of pulverized recycled aggregates were mixed with 20 ml of distilled water, this mixture is stirred with a glass rod for several minutes and then the pH measurement was made.

### **3. RESULTS AND DISCUSSION**

#### **3.1 Particle size distribution**

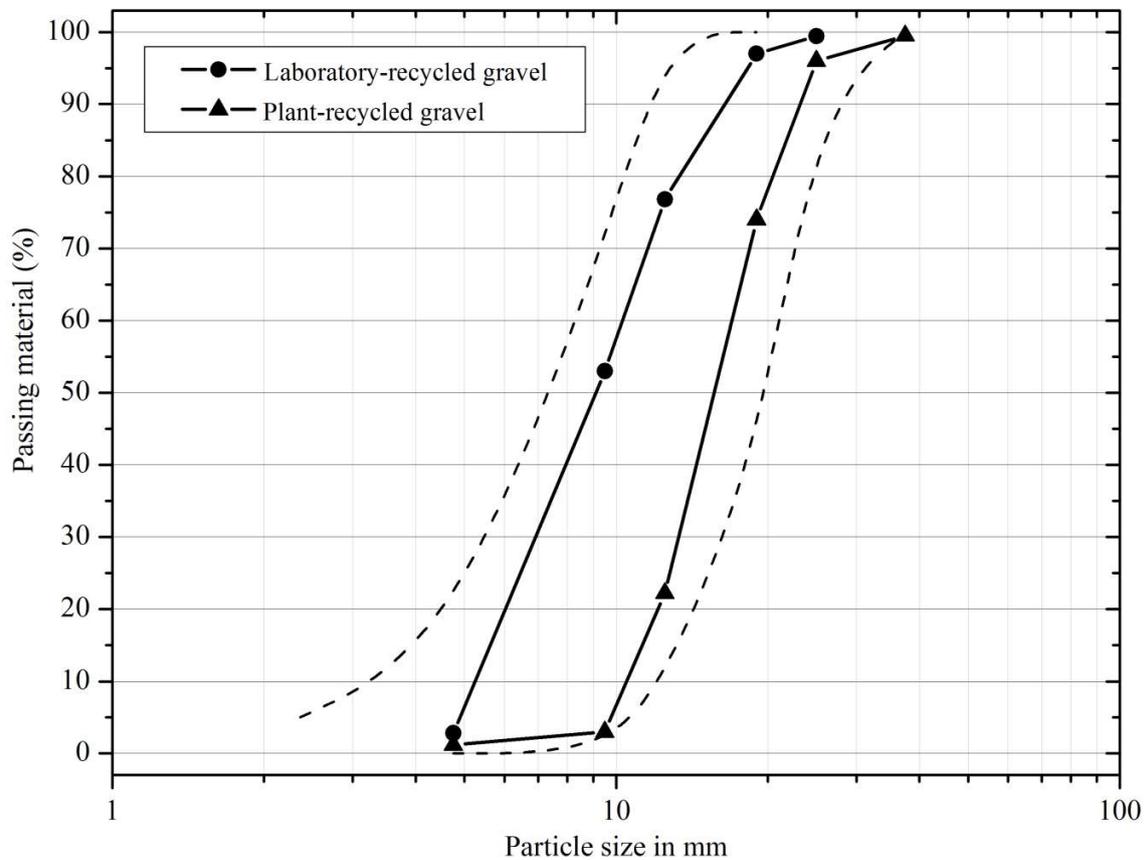
The granulometric curves were determined for both types of recycled aggregates (plant and laboratory), and were graphed considering the granulometric limits established in the NMX C-111-ONNCCE-2014 standard [8] (EN 12620:2008), which provides specifications and test methods for hydraulic concrete aggregates in the construction industry.

As already stated, the objective is to find alternative uses for these aggregates, since there is a large number of works worldwide, about the incorporation of recycled aggregates into new concrete mixtures, which indicate that it is possible to replace up to 50% of natural gravel by

recycled gravel of demolished concrete without compromising the quality of the concrete [9], therefore the main objective of this granulometric analysis is to know their size distribution and relate it to the chemical analysis, a second purpose was to determine whether the samples of these aggregates met the required size distribution of aforementioned standard.

Figure 2 shows that both plant-recycled gravel and laboratory-recycled gravel present granulometric characteristics within the recommended parameters for aggregates of a maximum nominal size of 25 mm; however, was the plant aggregate curve indicated a deficiency of 10-mm particles, which was attributed to a resistance to fragmentation of plant aggregates recycled from high-resistance or reinforced concrete. With respect to the granulometric composition of laboratory-recycled gravel, the curve is also almost straight for sizes close to 4 mm and up to 10 mm, which involves a larger amount of fine grains and is associated with lower recycled concrete quality, i.e., the concrete is easier to grind.

These results are in line with a study by Kobayashi and Kawano [10], who determined that aggregates recycled from high-resistance concrete present higher granulometric modules as compared with lower resistance concretes.



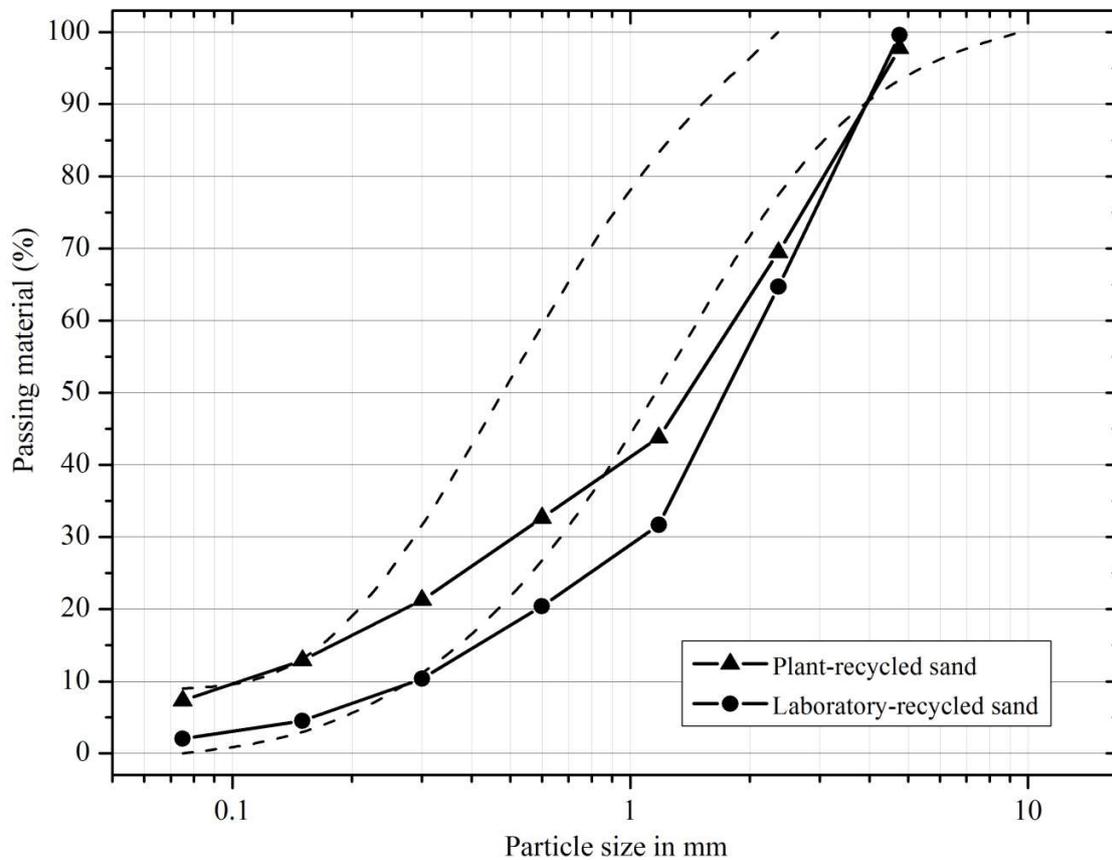
**Figure 2.** Recycled gravel particle size distribution

Additionally, it must be highlight that a larger number of particles (fragments) composed entirely by mortar (sand and cement paste) is readily apparent in plant-recycled gravel as compared with the number of fragments of original gravel or rock with adhered mortar [11], a condition that, as was previously stated, is associated with the quality of processed demolished concrete, i.e., higher-quality concrete has a larger proportion of cement and is more resistant. The interpretation of these results suggests the influence of the quality of the original concrete in the granulometry of the recycled gravel.



**Figure 3.** Above: plant-recycled gravel showing fragments entirely composed of mortar (sand and cement paste). Below: laboratory-recycled gravel with aggregates composed of rock with adhered mortar

Figure 4 compares sieving results of sands recycled in the plant and in the laboratory. The graphic shows that both sands fail to meet the Mexican norm, although their curves display continuous behavior and lack sudden changes of slope. In both sands a scarcity of particles close to 1 mm is evident. This behavior can be attributed to the fact that the cement paste and the mortar constituted by cement paste and micro aggregates adhered to millimeter particles increases the retention in meshes of greater aperture; this trend was also observed by Bianchini et al. [12], who analyzed different size fractions of recycled fine aggregates by X-ray fluorescence and determined that there are high contents of CaO in fractions of size between 2 and 4 mm.



**Figure 4.** Recycled sand particle size distribution

Curiously, plant-recycled sand presented higher contents of fine particles ( $< 75\mu$ ) than laboratory-recycled sand, which contradicts the argument that when the quality of the demolished concrete is high, the recycled aggregates will be larger and more resistant due to the resistance of adhered material; however, plant-processed sands undergo a more complex grinding and sieving process that entails higher fragmentation as a result of transportation and agitation [13], as opposed to laboratory sands, which were crushed in a single cycle and sieved by hand.

Both recycled sands do not comply with the size distribution required to make concrete, but even when they met the tolerances indicated, there is a consensus in the literature that the use of

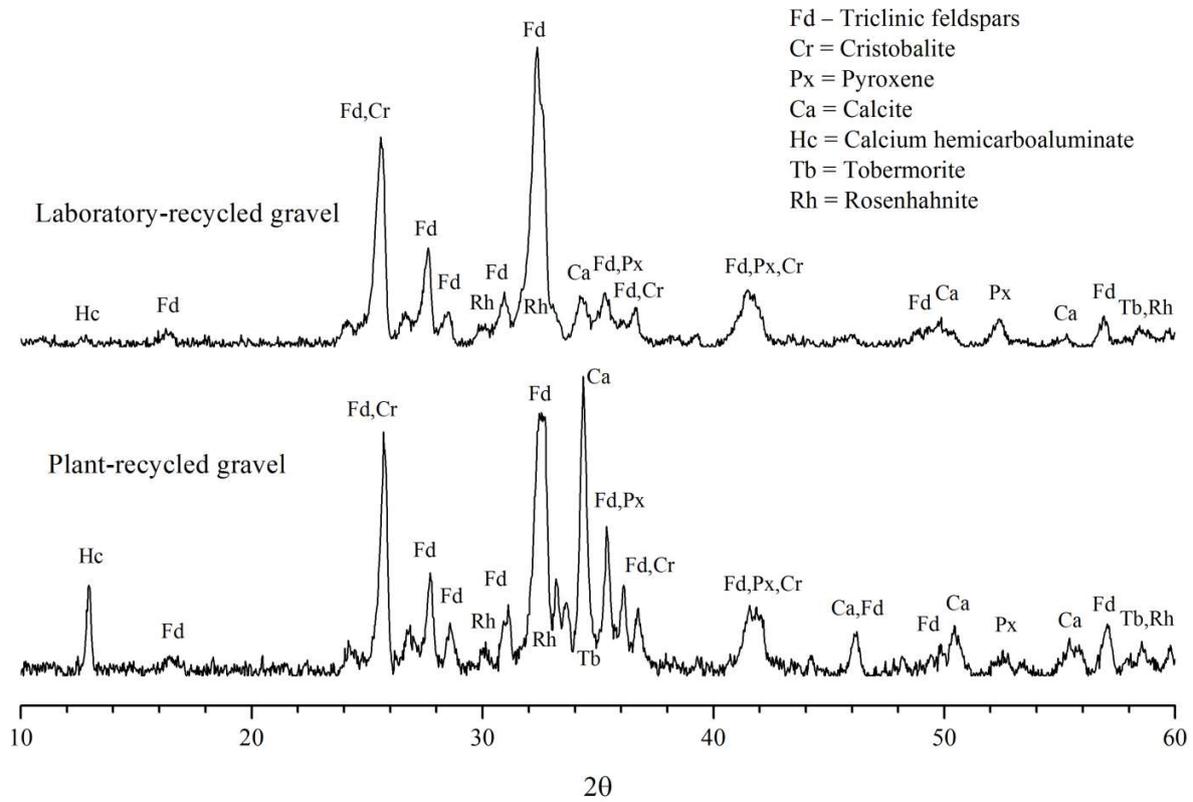
recycled sand in concrete production has a negative effect on the high content of cement paste which generates a high water absorption and low mechanical properties [14].

### **3.2 Mineralogical composition**

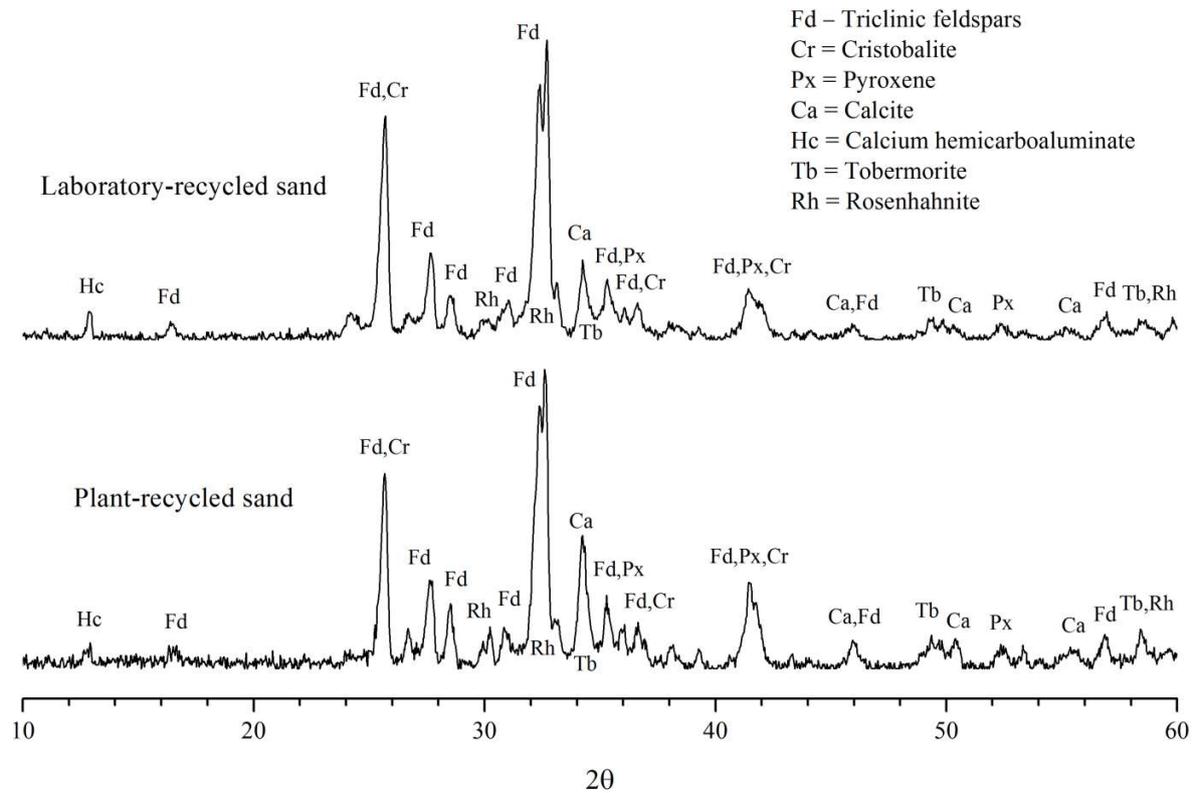
Figures 5 and 6 illustrate X-ray diffraction results from gravels and sands recycled in the laboratory and in the industrial plant. All of these patterns are very similar to one another; they present wide peaks and reflection overlapping typical of multiphase mixtures.

Phase identification was carried out automatically by Match! software, which determined the presence of different amounts of crystalline phases corresponding to original aggregates and adhered cement paste.

The identification of phases was carried out automatically by Match! Software, identifying the presence of different amounts of crystalline phases that correspond to the original aggregates and to the cement paste adhered to them. In this work the quantity of crystalline phases was not quantitatively determined, only its abundance was estimated according to the relative height (intensity) of the peaks [12], in table 2 the proportion of the phases is presented minerals inferred from the intensity of the main peaks.



**Figure 5.** X-ray diffraction patterns in recycled gravel samples



**Figure 6.** X-ray diffraction patterns in recycled sand samples

**Table 2.**

**Mineral phases present in recycled aggregates**

	Concretos Recicladados S.A.		Concrete from landfills	
	Plant-recycled gravel	Laboratory-recycled gravel	Plant-recycled sand	Laboratory-recycled sand
Feldspar	***	****	****	****
Calcite	***	**	***	***
Cristobalite	*	*	*	*
Pyroxene	*	*	*	*
Hemicarboaluminate	**	*	*	*
Rosenhanite	*	*	*	*
Tobermorite	*	*	*	*

Proporciones: \*\*\*\* mayor, \*\*\* mediana, \*\* menor, \* pequeña

**3.2.1 Minerals of the original aggregates.** The aggregates represent around 70-80% of the components of the concrete [15], therefore, the abundant minerals in all the analyzed samples (plant and laboratory) belong to the primary aggregates, in this case feldspars triclinics, of which we identified albite, oligoclase, andesine, and anorthite, which belong to the plagioclase group (Na and Ca feldspars), in addition to anorthoclase which is also a triclinic feldspar but of Na and K.

These feldspars are actually a solid solution, that is they have the same unit cell but with different amounts of Na, K, and Ca atoms, which slightly change the crystalline structure, hence the widening of the peaks marked with the letters Fd, which are in reality the sum of the reflections of the same crystallographic plane but of different feldspars.

Besides feldspars, an abundant type of silicate in the Earth's crust, all the samples contained small proportions of cristobalite and pyroxene. All of these mineral species, identified by their diffraction peaks, are considered constituents of intermediate and basic igneous rocks; therefore, they are assumed to correspond to the original rock aggregates used to produce the recycled concrete both in the laboratory and in the plant.

The minerals identified in all recycled aggregate samples reflects the local geological context, which evinces that these recycled aggregates contain rock materials extracted in the region [16]; according to the Mexico City geological and mining chart [17], there are numerous material banks and sources of gravel near the city, where aggregates with classifications such as andesite-dacite, andesite, and basaltic andesite have been extracted.

**3.2.2 Minerals of the cement paste adhered.** Quantified per diffraction peak intensity, calcite ( $\text{CaCO}_3$ ) was found in medium to minor proportions in all the studied recycled aggregates;

smaller amounts of calcium hemicarboaluminate and crystalline hydrated calcium silicates such as rosenhanite and tobermorite were also detected.

The significant presence of calcite was due to the carbonation of cement hydration products in the paste adhered to recycled aggregates, which consists mainly of portlandite  $\text{Ca(OH)}_2$  and C-S-H hydrated calcium silicates ( $\text{CaO-SiO}_2\text{-H}_2\text{O}$ ); these phases become carbonated as described by the following reactions (1 and 2):



It is important to note that no peaks of portlandite  $\text{Ca(OH)}_2$  were detected in any of the analyzed materials, although it should be present, as proposed by Liu et al. [19], who determined that calcium hydroxide  $\text{Ca(OH)}_2$  undergoes an accelerated carbonation when the samples are ground into fine particles for analysis, during this grinding the  $\text{Ca(OH)}_2$  is released from the cement paste and is exposed directly to the  $\text{CO}_2$  in the air, therefore part of the  $\text{CaCO}_3$  detected in the diffractograma, belongs to the carbonate generated after the grinding necessary for the powder diffraction technique.

It should be emphasized that an unknown amount of calcite is generated by the carbonation of the hardened cement paste during the useful life of the original concrete and during the storage time of recycled concrete.

It is worth mentioning that the presence of portlandite  $\text{Ca(OH)}_2$  is not ruled out, rather it is assumed that it is found in amounts lower than the detection limit of the X-ray diffraction technique, which is around 1% in minerals [20].

On the other hand, the calcium hemicarboaluminate detected is a phase formed in the first stages of the carbonation of cementitious materials, specifically it is the product of the decomposition of calcium monosulfoaluminate, a minor component of cement paste [21], another tentative explanation for the presence of this species, is that it was formed during the hydration of the cement due to the amount of  $\text{CaCO}_3$  used as a filler in cement production [22-23], in other words the calcium carbonate in the form of pulverized limestone, which is an additive allowed in the production of Portland cement, favors the formation of calcium hemicarboaluminate during the hydration of cement, in this case it is possible that mineral has been in the concrete before carbonation and the recycling process.

Regarding the identification of crystalline calcium silicates hydrated C-S-H (rosenhahnite and tobermorite), the main peaks of these species are not evident because they are overlapped by the intense peaks of feldspars and calcite, and however they were identified by its secondary peaks close to  $60^\circ$ . These minerals resulting from cement hydration reactions are found in small proportion in the 4 samples.

It should be mentioned that no X-ray spectrum presents the typical signal (wide bands) of the amorphous C-S-H gel, nor of the semicrystalline C-S-H whose signal is a double peak close to  $30^\circ$  [24], these results agree with those obtained by Evangelista et al. [13], who did not detect the presence of CSH by this technique.

Likewise, when visually comparing the diffractograms of the 4 samples analyzed (figures 5 and 6), it is noticeable that the diffraction peaks of calcite are more intense (high) in the recycled gravel sample of the Concretos Reciclados plant, this situation it is associated with the fact that these coarse aggregates, as already mentioned in the granulometric analysis section, present a greater quantity of fragments entirely formed by mortar, therefore they will have a greater quantity of carbonated cement paste. This abundance of calcite was not observed in laboratory-

recycled gravels, because during the sampling in landfills, only simple concrete was collected, which may have a lower content of hardened cement paste, but not the gravel sample of the plant, which contains fragments from reinforced concrete of higher quality, ie with more cement.

### 3.3 Chemical composition and pH

Table 3 reports the results of the elemental chemical analysis expressed in percentage by weight, in order to assess whether the compositional variation is consistent with the results of X-ray diffraction.

<b>Table 3.</b>				
<b>Results of the chemical analyses by EDS of recycled aggregate samples expressed as weight percentage.</b>				
	<b>Concretos Recicladados S.A.</b>		<b>Concrete from landfills</b>	
	Plant-recycled gravel	Plant-recycled sand	Laboratory-recycled gravel	Laboratory-recycled sand
Si	23.79	24.47	28.50	27.07
Al	6.80	7.20	7.27	7.35
Fe	3.71	4.61	4.00	3.96
Ca	16.50	13.19	8.47	10.46
Mg	1.13	1.12	0.91	0.60
K	1.33	1.19	1.69	1.71
Na	2.59	2.93	2.89	2.62
Ti	0.10	0.17	0.00	0.19
S	0.28	0.59	0.12	0.40
O	43.75	44.53	46.16	45.64
Total	100.00	100.00	100.00	100.00

The data from the EDS analysis show that the variation in the weight percentage of calcium attributed mostly to the cement paste adhered to the gravel and recycled sand, is consistent with the intensity of the calcite peaks in XRD, in other words higher Ca percentages in the chemical analysis (EDS), correspond to more intense calcite peaks in the diffractogram and vice versa. On

the other hand, the amount of silicon remains without significant changes in the 4 samples, as well as the intensity of the diffraction peaks of the feldspars (Si-rich), therefore it can be affirmed, that from the chemical-mineralogical view point, recycled aggregates have a composition inherent to their origins (igneous), which was enriched with calcium by the amount of mortar adhered.

From another perspective, to adequately address the pH measurement section, it is necessary to consider that a noncarbonated concrete has a pH value approximately 12.5, mainly due to the presence of calcium hydroxide formed in the process of cement hydration, and this value decreases below 9.5 during carbonation [25].

In the same way, it should be taken into account that when talking about the pH of the concrete, in reality it refers to the pH of the solution that fills the pores in the cement paste, so that the dissolved species in that solution can only come from the cement paste, since the aggregates by themselves are considered inert.

Taking into account the above, the pH measurements of the pulverized samples of recycled aggregates mixed with water (table 4), demonstrate the alkaline character of these materials, with values ranging from a very alkaline pH of 12.08 for the plant-recycled gravel sample, to 10.15 for the laboratory-recycled gravel sample.

**Table 4**  
**pH measured in water of samples of recycled aggregates**

	<b>Concretos Reciclados S.A.</b>		<b>Concrete from landfills</b>	
	Plant-recycled gravel	Plant-recycled sand	Laboratory-recycled gravel	Laboratory-recycled sand
pH	12.08	11.09	10.15	10.48

There are several possible explanations for the high alkalinity of the 4 samples of recycled aggregates, which were considered mainly carbonated according to the diffraction data. The first is that there are soluble alkalis (Na and K) and quantities of portlandite  $\text{Ca}(\text{OH})_2$  below the limit of detection of XRD that dissolves and release  $\text{Ca}^{2+}$  and  $\text{OH}^-$  ions maintaining high pH. Notwithstanding one of the limitations of this explanation is that it was not possible to identify the presence of portlandite with the techniques used, but it is assumed that it is present considering that the pH is higher than 10 in all tests.

The second possible explanation is that in addition to the dissolution of alkalis and  $\text{Ca}(\text{OH})_2$ , the dissolution/release of Ca ions and hydroxyls present in the calcium hemicarboaluminate  $\text{Ca}_4\text{Al}_2(\text{CO}_3)_{0.5}(\text{OH})_{13}\cdot 5.5\text{H}_2\text{O}$  also occurs [26], caused by the increase in the surface area that the sample undergoes when to grind for the experiment, that is to say it dissolves easier when it is finely divided. This last explanation was inferred by the correlation between the pH and the amount of calcium hemicarboaluminate in the samples, in other words the samples with the highest amount of hemicarboaluminate present a high pH.

In general, the pH data suggest that a recycled aggregate with greater amount of cement paste will be more reactive when mixed with water, because the concentration  $\text{Ca}^{2+}$  and  $\text{OH}^-$ , will increase by the dissolution/release of these ions present in certain phases of the hydrated cement (portlandite and possibly calcium hemicarboaluminate).

Finally, despite that the present study is based on two types of aggregates only (recycled in the laboratory and in an industrial plant), its results contribute to the knowledge base on the use of recycled aggregates in different applications according to their chemical and mineralogical composition. In this case, considering the amount of Ca in the chemical analysis and the alkaline pH, it is suggested that these materials (especially plant-recycled gravel) could be used in

geotechnical applications, such as the stabilization of clay soils, take account that the alteration of clay minerals in an alkaline medium occurs from pH values of 11.7 [27].

#### 4. CONCLUSIONS

In this work, 4 samples of recycled aggregates from construction and demolition waste from Mexico City, gravel and sand from a recycling plant, and gravel and sand recycled in the laboratory were characterized.

The mineralogical characterization by XRD reveals that the minerals present in the recycled aggregates analyzed (plant and laboratory), are triclinic feldspars, cristobalite and pyroxene (silicon-rich minerals), which correspond to the original rock aggregates, as well as variable amounts of calcite ( $\text{CaCO}_3$ ), product of the carbonation of the cement paste adhered to these aggregates, and in smaller proportion of calcium hemicarboaluminato, rosenhahnita and tobermorita, phases that are also compose the agglutinating matrix

Likewise, the results of the chemical characterization show quantitatively that only the calcium varies significantly in all the samples, this element is attributed mainly to the minerals of the cement paste, therefore from the chemical-mineralogical view point it can be affirmed that the recycled aggregates possess a composition inherent to their igneous origin, which is enriched with calcium by the amount of mortar adhered.

It was determined that the quality (quantity of cement) of the original concrete that was processed, has great influence on the granulometry and the chemical-mineralogical composition of the recycled aggregates, since there will be different quantities and qualities of cement paste adhered to these aggregates of according to size, for example, the proportion of calcium increases in plant-recycled gravel because their resistant cement paste does not easily fragment, consequently aggregates entirely formed by mortar are produced during recycling.

Finally, the alkaline pH values (above 10) in all samples of recycled aggregates indicate that there are enough soluble species to maintain an alkaline pH even though the cement paste adhered to these aggregates is mostly carbonated, for this reason It is suggested that these materials could be used in geotechnical applications, such as the stabilization of clay soils, which would represent an innovative application for this type of materials.

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