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Recycled concrete: a review.

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RESUMO
A geração de resíduos sólidos de concreto, considerados como entulho, está se tornando um problema ambiental. Este material de construção é composto principalmente por cimento Portland (CP), mas um dos problemas é a sua alta temperatura de fabricação, que gera poluentes. O uso de agregados triturados originados da demolição do concreto é aproveitável para a elaboração de Concreto Reciclado, um material que pode diminuir custos, diminuir a contaminação e tornar a edificação mais econômica. Porém, a elaboração de concreto reciclado enfrenta a busca por traços otimizados para se alcançar um maior desempenho mecânico sob solicitações estáticas e dinâmicas. Este artigo faz uma revisão dos avanços internacionais sobre este assunto.
Palavras Chave: Concreto reciclado, Resíduos sólidos, Cimento Portland, Agregados.

ABSTRACT
The generation of solid residues of hydraulic concrete, also considered waste, is turning into an environmental problem. The construction material primarily manufactured is Portland cement, but one of the main problems is its high manufacturing temperature which generates pollutants. The use of grinded aggregates that come from the demolition of hydraulic concrete is used to generate recycled hydraulic concrete, a material that could lessen costs, decrease pollution and cheapen construction. Nevertheless, the elaboration of recycled concrete faces the search for optimal designs in order to achieve the highest mechanical performance under static and dynamic requests. This work reviews international advancements in this field.
Keywords: Recycled concrete, Solid residues, Portland cement, Aggregates.

RESUMEN
La generación de residuos sólidos de concreto hidráulico, considerados como desecho, está convirtiéndose en un problema medioambiental. El material de construcción mayormente fabricado es el cemento Portland (CP), pero un problema es su alta temperatura de fabricación, que genera contaminantes. El uso de agregados triturados provenientes de demolición de concreto hidráulico se aprovecha para generar Concreto Hidráulico Reciclado, un material que puede abatir costos, disminuir la contaminación y abaratar la edificación. Sin embargo, la elaboración de concreto reciclado se enfrenta a la búsqueda de diseños óptimos para lograr el mayor desempeño mecánico bajo solicitaciones estáticas y dinámicas. En este trabajo se hace una revisión de los avances internacionales en esta temática.
Palabras Clave: Concreto reciclado, Residuos sólidos, Cemento Portland, Agregados

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1. INTRODUCTION

Among many other fields, environmental preservation is an area of civil engineering that could be supported by the use of recycled concrete, which: minimizes the discharge of solid residues that pollute the environment, reuses materials that are considered waste and that do not have a significant cost, and innovates material design to achieve the maximum mechanical performance under static and dynamic requests that allows for health improvement of those who use buildings constructed with these materials. Recycled concrete also preserves the environment as it prevents pollution from solid residues, decreases the emissions of COx into the air that we breathe and prevents the unnecessary extractions from quarries of geological materials preserving landscape architecture and the endemic flora and fauna.

Each profession is morally obligated and responsible to contribute to the best of its ability to the improvement and preservation of the environment. Recycling concrete is therefore an important research topic in order to prevent global warming. Its design, elaboration, durability, performance, economy and viability are researched.

The employment of recycled construction materials dates back to the 1940's as Europe had excessive amounts of debris due to bombardments. This debris was used as quarries for building reconstruction with successful results. The countries most affected were the United Kingdom and Germany. The publications of that time, mainly British, German and Russian, informed of the use of debris for the construction of new civil work. Much of the debris comprised ceramic material (bricks, ceramic from sanitary services), natural stone material, plastics and rubbers (Hoffmann et al., 2012; Kulakowski et al., 2012) and hydraulic concrete, which later used aggregates such as slags, ashes, and silica fumes (González-Fonteboa et al., 2009). Hydraulic concrete arrived to the United States at the end of the 21st century (Torres et al., 2014), and subsequently the United States began further investigation on recycled concrete as well. The first report of recycled concrete was done in the former Union of Soviet Socialist Republics by P. Gluzhge in 1946, shortly after the Second World War.

Following Gluzghe's research, the first studies carried out in the United States recommended the use of recycled hydraulic concrete from road infrastructures or rigid pavement, and in a secondary manner the use of recycled concrete from buildings such as homes. This research mentioned that these infrastructures and buildings could be contaminated with sulphur products since plaster was used for wall coverings (anhydrous or semi-hydrated calcium sulfate). The new concrete could be attacked by sulfates and this damages the steel reinforcement soaked in the hydraulic concrete. The recycled hydraulic concrete was mainly used in asphalt mixtures used for concretes, replacing the stone aggregates, the problem of which was the lack of electric affinity with asphalt materials (Harek et al., 1971; Buck, 1972). For a long time, the idea prevailed that natural acid stone materials (silica base: ignimbrites, dacite, andesite, plagioclases, orthoclase, quartz, cristobalite, tridymite, etc.) presented negative superficial electrical charges, while the basic or alkaline stone materials (ferromagnesian: basalts) presented positive superficial electrical charges. In recent research, it has been stated that all natural stone aggregates (volcanic and shredded: sandstone, granite, marble, dacite, andesite, rhyolite, limestone, dolomites, quartz, basalt) have negative electrical charges (Rodríguez Talavera et al., 2001).

Keeping in mind the aforementioned, it is extremely important to know if there will be affinity in the manufacture of asphalt mixtures with anionic or cationic emulsions. Recycled concrete was also elaborated with tyre residues as is done with asphaltic pavements (Kardos et al., 2015). The intensity of the aggregate's surface charge, combined with the intensity of the charge of the emulsion agent, could strongly influence the break speed, particularly in the case of cationic emulsions. The calcium and magnesium ions present on the surface of the aggregate could react with, and destabilize, certain anionic emulsions, accelerating the break speed of the emulsion (Carrasco, 2004). This superficial electric affinity problem does not happen with recycled hydraulic concretes with ceramic matrixes.

2. BACKGROUND

In order to recycle solid waste materials, such as garbage and residues in the case of demolished or collapsed concrete, reusable for the elaboration of new concrete mixtures, the following objectives must be accomplished: a) the reuse of solid waste, decreasing the amount of residues or waste that harm the environment and consequently humans as well, for example the problem with leachates; b) the design, innovation and elaboration of new ecofriendly construction materials; c) the conservation of natural minerals from quarries, which reverts back to the protection, non-exploitation and preservation of the natural habitat of native flora and fauna, conservation of the landscape architecture and geoparks, since mineral resources are non-renewable; and, d) decrease atmospheric pollution by providing a material, the production of which causes emissions of CO and CO2, a new purpose. The production of volcanic stone aggregates being extrusive igneous rocks, such as the regional ones from Michoacán, Mexico, implies that they are the product of volcanic events and the magmatic ejections are a source of oxidized sulfur, SOx. The volcanic activity constitutes an important source of SOx emissions to the atmosphere, being the main source of sulfur in the stratosphere (Amigo Ramos, 2000; López et al., 2015; Ruggieri, 2012). The CO and CO2 compounds are materials that due to photosynthesis can turn into O2; however, there is not a process that will absorb sulfur compounds and turn them into oxygen.

The manufacture of CP produces approximately the same weight in carbon compounds released into the atmosphere, such as CO and CO2; so, the recycling of concrete also reduces the carbon footprint in the atmosphere. Latin America does not stand out for its great contribution to global contamination.

In 2002, the main source of greenhouse gas emissions in Mexico was the energy sector, responsible for approximately 70% of emissions. Other industrial processes, such as the production of cement, glass, steel, paper, food and beverages, among others, contributed with approximately 9% of the total emissions of greenhouse gases in the country (Climatic Change, 2009). 40% of carbon dioxide produced by a typical family comes from the motor vehicles that run on fossil fuel and from the construction of houses (https://www.veoverde.com/2014/01/llegaron-las-viviendas-sustentables-a-mexico/).

Concrete is one of the most manufactured and used materials in the world for the construction of civil and military works, but it is also a generator of large volumes of solid residues associated with demolition and waste processes (Valdés et al., 2011). In order to reduce the climatic change and environmental production, the signing of the Kyoto protocol was pursued; it was negotiated in 1997 and enforced in 2005. The protocol intended for 37 developed countries to reduce their greenhouse gas emissions to 5% by 2012, with respect to their emission levels in 1990. Mexico did not sign as it was not considered a developed country.

The protocol has resulted in developed countries initiating policies focused on the reduction of such volumes of pollutants released into the atmosphere (Alonso et al., 2007) through its reuse, decrease or recycling (Debieb & Kenai, 2008; Rolón et al., 2007; Valdés et al., 2009).

Studies conducted in the European Union (Etxeberria et al., 2007; Vázquez et al., 2004; http://ficem.org/publicaciones-CSI/DOCUMENTO-CSI-RECICLAJE-DEL-CONCRETO/RECICLAJE-D-CONCRETO_1.pdf; Jianzhuang et al., 2012;

http://www.concretosreciclados.com.mx/; http://www.veoverde.com/2013/11/concretos-reciclados-otra-apuesta-mexicana-por-el-ambiente/) have been able to establish that the production of construction residues rose to around 900 million tons/year, as is shown in the summary of Table 1. Research done in Spain, Germany, France and England, all countries that lack an abundance of quarries with natural mineral stone aggregates, has been able to determine the viability of the reuse of hydraulic concrete from construction as granular material, even more so if there exists a lack of these materials. Their aim is toward those materials that require fewer fossil fuels for their manufacture, transport and recycling, which would reduce the necessary energy for their reuse.

It can be observed that in regards to the quantity or per capita recycling, Australia stands out with the highest amount, 25.78 ton/inhabitant. Regarding the amount of recycled concrete with respect to a country's territory, theoretically, the bigger the territory the more construction is done and therefore more residues would be present. However, Taiwan stands out with 1862.15 tons per km2 of territory, having the highest index of the abstract. Several countries do not have an accurate record yet.

Much has been said about the earthquakes that struck countries such as Turkey, Afghanistan, and Nepal, but there are no records in the indexed literature of the quantities used of recycled concrete, without forgetting that these countries still maintain the tradition of having ceramic and/or adobe walls, with large elasticity modules for the absorption of dynamic energies.

The global production of hydraulic concrete is estimated to be around 25 billion tons per annum.

Due to environmental contamination and climatic change, it is important to initiate the creation of collective conscience in lesser developed countries in order to reduce the extraction of stone materials from natural environments, as well as to reduce the accelerated depletion of aggregate reserves that originate both from river streams and quarries (Rhakshvir & Barai, 2006; Montoya et al., 2005). The demand of natural resources and the lack of raw materials are important; consequently, the need to preserve and protect the environment from an ecological imbalance makes the technique of recycled concrete (Oikonomou, 2005) an important activity in construction (Aguilar et al., 2005).

Previous research has demonstrated that the physical and mechanical properties of recycled hydraulic concrete, comprised by recycled aggregates in its matrix, could guarantee resistance and mechanical performance (Topcu, 1997; Topcu & Sengel, 2004; Topcu & Guncan, 1995). Studies derived from specific applications in civil works show that on several occasions concrete residue is neither enough nor efficiently employed. This concrete residue could also be employed to produce pre-manufactured elements of concrete, such as blocks, insulating materials, lightened materials, and panels.

For successful recycling, several variables should be considered in the design of new concrete mixtures: the percentage of recycled material, the percentage of recycled coarse ore, the percentage of fine material, the water/cement relation, the density of recycled material, the use of thinners, shrinkage (workability), mechanical resistance, and homogeneity (Chang et al., 2011). The microstructure study of recycled concrete presents new challenges as the interfacial zone (ITZ) has two zones difficult to identify according to the age/hydration (Kong et al., 2010; Li et al., 2012): old and modern rapid-setting concrete, with different compositions, porosities, densities, age, resistivity, hydration and hardness.

Table 1. Abstract of recycled concrete. 1. Millions of tons of recycled concrete (CSI Recycling Concrete Full Report, 2007); 2. Country territory in km^2; 3. Inhabitants in millions; 4. Relation of the recycled concrete in millions of tons per capita; and, 5. Relation of tons of recycled concrete produced per km^2 of territory.

Country	1	2	3	4	5
Germany	120.00	357,121	80	1.5	336.02
Argentina	5.50	2 780 400	43	0.13	1.99
Australia	550.00	7,692,024	21.5	25.58	71.50
Austria	22.00	83,371	8.3	2.65	266.88
Belgium	14.00	30,510	10.4	1.36	458.87
Brazil	50.00	8,500,000	200	0.25	5.88
China	200.00	9,600,000	1,300	0.15	20.83
Colombia	13.00	1,141,748	47.4	0.27	11.38
Costa Rica	0.50	51,100	5	0.10	9.78
Denmark	5.00	43,098	5.6	0.89	116.01
United States	335.00	9,826,675	316	1.06	34.09
Spain	39.00	504,645	47.1	0.83	77.28
Finland	1.60	337,030	5.4	0.3	4.74
France	25.00	675,417	66	0.38	37.01
Holland	26.00	41,526	16.8	1.55	626.11
Ireland	17.00	84,421	6.2	2.74	201.37
Israel	7.50	22 145	8.6	0.87	3.39
Italy	40.00	301,338	59.4	0.67	132.74
Japan	77.00	377,835	126.7	0.61	203.79
Luxembourg	2.70	2,586	0.54	5	1044.08
Mexico	30.00	1,964,375	119	0.25	15.27
Portugal	4.00	92,391	10.6	0.38	43.29
United Kingdom	70.00	243,610	63.2	1.11	287.34
Czech Republic	9.00	78,866	10.5	0.86	114.12
Switzerland	7.00	41,290	7.9	0.89	169.53
Sweden	1.20	449,964	9.6	0.13	2.67
Taiwan	67.00	35,980	23.1	2.9	1862.15
Thailand	10.00	513,115	65.5	0.15	19.49
Worldwide	900.00	150,386,640	7000	0.13	5.98

The reduction method for the size of the hardened hydraulic concrete in order to obtain gravel could result in loss by pulverization, aggregate sizes ≤ ¼ of an inch (6.4 mm), porous areas with their corresponding forms, sizes and distribution in the pores of the matrixes, which increase the superficial area increasing the demand of CP in the new mixture (Koeu et al., 2011; Gómez-Soberon, 2012). This is an undesirable morphology in the grinded particles where the dimensions regarding the X, Y and Z axes are very different among themselves, producing elongated or semicircular shapes (Eguchi et al., 2007). In order to avoid that the aggregates in the concrete present problems such as the ones described, the product of the grinding, fine and thick, should be characterized to make optimal concrete designs; some countries already have a code for recycled stones (Martín-Morales et al., 2011). Another parameter to be considered is the percentage of natural stones that could be replaced by recycled material (Etxeberria et al., 2007), the use of cement per m^3 of hydraulic concrete and the mechanical resistance are functions of this percentage (Marie & Quiasrawi, 2012). Some mixtures only replace thick aggregates with recycled material, while others only replace fine aggregates with recycled material (Evangelista & Brito, 2007; Raoa et al., 2007). The quality and properties of the aggregates depend on the mother rock or concrete from which they originate, the stronger the resistance of the primary concrete the stronger the resistance of the recycled aggregates that come from the original concrete (Kou et al., 2012). However, there is also the possibility that the primary concretes come from different origins. Other mixture designs use both types of recycled aggregates, some authors work with specific percentages of each aggregate (Mas et al., 2012). The variations are designed and elaborated taking the mechanical design properties into consideration, which are sought in recycled concrete (Padmini et al., 2009; Tabsh & Abdelfatah, 2009).

The use of CP depends on the design method, the security factor, the material type, the seismic coefficient, the soil quality, and the construction use. There are no universally recognized methods to design mortars or concretes with aggregates from recycled concrete, but mortars have been successfully manufactured with recycled material (Abbas et al., 2009).

The design of concrete mixtures started at the end of the 19th century and beginning of the 20th century with Dr. Duffus Abrams (Abrams, 1918). Until the end of the 20th century, hydraulic concrete was designed based on the mechanical resistance to compression, which is the index property of the concrete; however, that concept changed at the beginning of the 21st century. Due to concrete performance, its useful life, and the need for less maintenance, the design of concrete mixtures takes into consideration durability criteria (Kwan et al., 2012; López Celis et al., 2006), identifying resistance and the speed of ultrasonic pulse as quantifiable parameters.

Concrete mixtures with recycled material are evaluated from the viewpoints of mechanical performance, physical performance, durability (Casuccio et al., 2008), forms of failure (Liu et al., 2011), fluidity, workability and shrinkage (Guneyisi, 2010), age and hydration of the cement (Katz, 2003), and the degree of compaction that could be achieved with vibratory methods or with special self-compacting cements (Kou et al., 2009).

Mechanical performance is usually evaluated by destructive testing with simple compression (Xiaoa et al., 2005) if there are cubic or cylindrical specimens. However, if there are only splinters with approximate dimensions of 10.0 cm, the Point Load Method can be used for those samples that have not been carved, simple tension and indirect tension, bending or modulus of rupture. The modulus of rupture is the index value for the design of hardened pavements (Lye et al., 2016). The evaluation of the recycled concrete is also done with the use of test methods that are not destructive and that do not require material preparation. They can be repeated and do not cause damage to the material; the electrical resistivity and speed of ultrasonic pulse are the most common (Park et al., 2005). In order to improve hydraulic concrete mixtures, security factors and reduction of the A/C relations are used with a prolonged curing period through immersion or sprinkling (Fonseca et al., 2011). Another way to influence modification of the properties of recycled concretes is through the use of additives and aggregates or cement replacements with materials that have pozzolanic activity. Alkaline activated concretes can be manufactured with aggregates from the recycling of hydraulic concrete (Kathirvel et al., 2016)

3. PRESENTLY

The most meticulous problem nowadays relates to greenhouse gas emissions and the actions taken to reduce them.
Work is being done to come up with proposals that help with the reduction of emissions and residues to the atmosphere.
The development of concrete manufacturing using stones (rocks) from the recycling of concrete generally has been sufficient in order to produce a new material with mechanical performance and durability that complies with international standards. Perhaps the main disadvantage is the porosity of the thick and fine aggregates produced by grinding, which has been solved by taking into consideration the following elements for new mixture designs. Firstly, the reduction of the water/cement relation should favor the durability and help obtain the sufficient mechanical resistance. Its resolution is done using thinners, super-thinners or water-reducing admixtures (aggregates indicated in ASTM C-494) that obtain workable and fluid mixtures. Secondly, the use of agro-industrial waste that presents pozzolanic activity, aluminosilicate-rich, that "fills" the gaps in the hardened paste (recrystallization in the pores densifying the matrix), calcium oxalates such as weddellite and whewellite have demonstrated that they perform the same role as additives to concrete (Torres et al., 2010; Torres et al., 2010 bis; Del Valle et al., 2015). The hydrated and hardened concrete, even the containers of recycled concrete demolished in 2011 and constructed in the 60's that remained outdoors during the rainy season formed new links among them, solidifying and making it had to break them by hand. The use of residues with pozzolanic activity also indirectly solves the accumulation of the other solid residues that pollute and take up space, the use of aluminosilicate-rich aggregates that increase the mechanical performance of the new mixtures, mixtures that increase the protection of the reinforcement steel soaked in them when densifying, reducing the attack by carbonation in concretes and thus also the corrosion in steel. Other ways of preventing corrosion in reinforcement steel in concretes is the use of stainless steel, which financially does not seem affordable, but significantly decreases the maintenance costs and increasing durability (Pérez Quiroz et al., 2014). The results of the physical and mechanical properties obtained from the additions, replacements and aggregates used in new mixtures of hydraulic concrete and mortar with cement bases and line, in a fresh and hardened state, show the veracity of these statements (Martínez et al., 2015; Bernabé, 2015 & 2012; Jacobo, 2014; Guzmán, 2014; Villicaña, 2014; Arreola, 2013; Zalapa, 2013; Contreras, 2013; Figueroa, 2013; Campos, 2013; Flores, 2013; Arguello, 2012; Gómez Zamorano et al., 2004; Moreno et al., 2004). And thirdly, the addition of chemical pozzolanic products of industrial purity level that can be activated at friendly temperatures, geopolymer materials (Rubio et al., 2014 Patent; Rojas, 2013; Medina, 2011) or alkaline activated materials are needed.
Currently, multiple solid residues are being experimented on as aggregates, which could have organic origins such as fibers, husks and seeds; additions that are residues from other industrial processes such as the ash from cane bagasse, mineral carbon ash, ashes from the elaboration of artisanal ceramic materials done with clays, metallurgical and steel production slags are being considered as well.

4. DISCUSSION

Table 1 shows that Australia is the country that recycles the largest quantity of tons per capita, while Taiwan is the country that recycles the most tons of concrete territory-wise. In the same table that lists the information on 28 countries, Mexico ranks in eleventh place indicating that we are far from using all our demolished concrete, but the effort made is important and sustainable, and shared by the community.

The use of recycled concrete is more common in Europe, maybe due to the lack of natural mineral aggregates. In Latin America, specifically Mexico, there is a continuous search for a sustained use of the materials considered solid waste that allow a response to environmental preservation, as well as to the search and innovation of additives, methods, techniques and processes that improve the mechanical processes of recycled concrete.

Another point to be mentioned is the sustained and continuous work done in the new design of hydraulic concrete by durability indexes, to prolong the useful life of the concrete structures, leading to the reduction of the demolition of the hydraulic concrete.

The reuse of solid residues has also conducted discoveries of properties that have allowed their addition to the mixtures of concrete/mortar, modifying some of their properties in favor of durability.

5. REMARKS

The use of recycled material prevents the accumulation of collapsed or demolished concrete that need to be removed or transported to dumping grounds of solid residues, with the corresponding fuel expense for its transportation. The accumulation of these solid residues has also caused changes in landscape architecture by modifying the morphology of the surface or topography of the reception zone of the demolished material.

The use of aggregates that originate from recycling allows a decrease in the amount of pollution emissions into the atmosphere.

The recycled material allows avoiding the overexploitation of quarries, preserving the landscape architecture and promoting specialized geological tourism which helps in the preservation of the endemic biota, diminishing the environmental impact of the extractions and the fail forms due to the slipping of material banks close to the population centers, as well as recharges to groundwater reserves.

6. CONCLUSIONS

Recycled concrete can solve the problem of lack of stone aggregates as well as protect their quarries. It clarifies if aggregates do not comply with current standards, such as the case of volcanic foam or pumicita. The use of aggregates that originate from recycled concrete also allow for these to be placed saturated in the mixtures and thus initiate the internal curing of the new mixtures of recycled concrete.

Stone aggregate obtained as a result of the demolition of concrete may not have ideal conditions, but there is also the fact that several locally existing natural mineral stone aggregates do not comply with existing recommendations in the current construction standards. Contractors, engineers and architects look for ways to make the most of recycled concrete achieving significant mechanical performances.

There is still much to be studied on recycled aggregate, but it is possible to obtain performances of 350 MPa in recycled concretes if the stones are measured correctly, the A/C relations are reduced, and if additives that modify the rheology of the fresh mixtures for their placement and simultaneously help to achieve the resistance are added.

Simultaneous to the design and elaboration of recycled concrete, the possibilities of the additions of other materials that modify the properties of the concretes elaborated likewise should be explored, achieving successful and economic conditions.
In the interest of preventing carbon emissions, stopping construction would mean putting a stop to the increase of infrastructure and the convenience of a country's inhabitants, but by not doing anything we appear to be accomplices. Therefore, alternatives are being sought for the production of construction materials that are the result of the use of materials that have turned into waste, residues and industrial garbage. This engages us in the search of modifying alternatives for the properties of new materials.

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