Molienda mecánica por alta energía de minerales mexicanos para producir concreto de alto desempeño (CAD)

High energy milling (HEM) of Mexican minerals to produce high performance concrete (HPC)

María Fuentes^{1*}, Araceli Zúñiga**, Manuela Díaz**, Enrique Rocha***, Sebastián Díaz*

* Instituto Politécnico Nacional, Centro de Investigación e Innovación Tecnológica. MÉXICO

** Instituto Politécnico Nacional, Departamento de Ingeniería Metalúrgica. MÉXICO

*** Universidad Politécnica de Victoria, Tamaulipas. MÉXICO

Fecha de Recepción: 27/03/2014

Fecha de Aceptación: 02/11/2014

PAG 256-269

Resumen

Se caracterizaron química, física y mineralógicamente agregados minerales finos mexicanos, tales como: ceniza volante, microsilíce, humo de sílice, escoria granulada de alto horno (EGAH) gruesa, fina y refinada para su dosificación con cemento Portland compuesto (CPC) en su estado normal y refinado por molienda de alta energía (HEM), con el objetivo de fabricar un concreto de alto desempeño (CAD), partiendo de subproductos industriales. Los materiales fueron acondicionados con tamaños menores a #200 mallas (75µm) y algunos con partículas del orden submicrométrico para analizar el aporte en la resistencia a la compresión dentro de las mezclas. Una vez caracterizada la materia prima se determinaron los parámetros experimentales para reducir los tamaños de partícula mediante HEM del cemento Portland compuesto y la escoria granulada de alto horno. Los productos de molienda, así como los demás materiales cementantes fueron caracterizados por: difracción de rayos X (DRX), microscopía electrónica de barrido (MEB) y absorción atómica. Se identificaron las fases presentes en dichos materiales, detectando una modificación en el porcentaje de las fases Alita C₃S y Belita C₂S favoreciendo la resistencia a la compresión, especialmente al moler el CPC durante 30 min por HEM. Los ensayos de resistencia a la compresión de las probetas del CAD obtenidas comprueban que la mayor resistencia a la compresión se alcanza usando humo de sílice HS.

Palabras claves: Molienda por alta energía (HEM), concreto de alto desempeño (CAD), cemento Portland compuesto (CPC) y agregados finos mexicanos

Abstract

In order to produce high performance concrete (HPC), fine Mexican mineral aggregates were characterized using chemical, physical and mineralogical procedures. Used materials included fly-ash, micro silica, silica fume, and coarse, fine and refined ground granulated blast furnace slag (GGBS), which were then dosed with Composite Portland Cement (CPC) in three forms: (1) commercially as-received, (2) as-screened and (3) after being high energy ball milled (HEM), i.e., as-milled. The materials were conditioned with less than 200 mesh (75µm) particles and with submicron particle sizes in order to analyze their contribution to the compressive strength of the paste. After characterizing the raw materials, the experimental parameters for reducing particle sizes by HEM - CPC and GGBS were determined. Milled products and other cementitious materials were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and atomic absorption analyses. Different materials phases were identified, thus observing a change in the mass percentage of Alite C₃S and Belite C₂S, which promote the compressive strength of the specimens produced, provided that the CPC has been ground by HEM for 30 min. Silica fume was proven to be the best aggregate, which triggers the compressive strength of the specimens prepared.

Keywords: High energy milling (HEM), high performance concrete (HPC), composed Portland cement (CPC), and Mexican fine aggregates

1. Introduction

High performance concretes (HPC) are composed of essentially the same materials as conventional concrete, with the significant difference of the proportions and conditioning of fine aggregates, and the use of special additives that are responsible for strength and durability. In turn, these characteristics may vary because they are based on the structural requirements of the masonry work, and they depend on environmental restrictions as well (Rivva, 2000).

Among the fine aggregates used to produce HPC, the following were included: ground granulated blast furnace slag (GGBS), fly-ash (FA), micro silica (MS), silica fume (MF) and silica sand.

¹ Autor de correspondencia / Corresponding author:

Instituto Politécnico Nacional. Centro de Investigación e Innovación Tecnológica, Cerrada de CECATI S/N, 02250, México, D.F. Tel. 57296000, ext.68313

E-mail: sediazt@ipn.mx

These materials have latent cementitious properties which, together with their high chemical silica (SiO_2) content and fineness, increase the concrete's compressive strength (Martínez, 2011).

The company of Altos Hornos de México S.A. de C.V. (AHMSA), located in Monclova, Coahuila, produces tons of granulated slag (GGBS) each month, which is considered as "waste" and represents 10wt% of the pig iron produced in the blast-furnace. When this slag is drastically cooled and granulated, it turns into a relevant industrial subproduct due to its intrinsic cementitious properties. Therefore, not only the cement industry is benefited by the recycling of this subproduct, but the ecological system itself (Pierre, 1998). Currently, GGBS is globally recognized as a total or partial replacement material for the OPC, given its cementitious properties and eco-friendly manufacturing (Escalante, 2002). Other national materials that are considered industrial subproducts due its high content of pozzolan properties are fly-ash, micro silica and silica fume.

While fly-ash (FA) is generated from the coal gasification process in thermoelectric plants, micro silica (MS) and silica fume (SF) are obtained from the reduction of quartz (SiO_2) by coal in electric arc furnaces, being fineness practically the only difference between them. Consequently, these materials are considered potential industrial subproducts, since their physical and chemical properties increase the compressive strength of concrete manufactured with composite Portland cement (OPC) (Lorenzo, 1993, Valdéz et al., 2007).

The present study deals with the technological feasibility of Mexican subproducts recognized as fine aggregates, for their use as alternative replacement and conditioning materials of OPC. Thus, the aim is analyzing the effect of the presence and concentration of different fine aggregates such as: ground granulated blast furnace slag (GGBS), fly-ash (FA), micro silica (MS), and silica fume (MF) to produce a type of high performance concrete (HPC).

2. Experimental Procedure

The methodology established to produce a HPC type using Mexican mineral resources consisted of four stages:

- 1. Selection and conditioning of the raw material.*
- 2. Characterization of the milling products.*
- 3. Mixture design.*
- 4. Compressive strength of HPC mixtures.*

The used cementitious materials had particle sizes of less than 200 mesh ($75\mu\text{m}$), except a GGBS mixture which had less than 60 mesh ($250\mu\text{m}$). Table 1 shows the experimental data for these mixtures.

Tabla 1. Parámetros de optimización de mezclas para CAD
Table 1. Mixture Optimization Parameters for HPC

Materiales/Materials	Cantidad/ Quantity
CPC	70% masa
CPC-refinado/ <i>Refined CPC</i>	30% masa
Cementante/ <i>Cementitious</i>	254 g.
Mezcla de Arenas/ <i>Sand Mixture</i>	1222.3 kg.
Agua des ionizada/ <i>Deionized Water</i>	297 ml.
Aditivo policarboxilato (PC)/ <i>Additive polycarboxylate (PC)</i>	50.4 g.

Once the mixture parameters were established, the following parameters were considered during the manufacturing:

- 3.3 Specific weight: in accordance with the ASTM C-138 standard (ASTM, 2012) to monitor its rheology.
- 3.3 Fluency: it is defined here as the percentage variation of the diameter of the base of a conic mold.
- 3.3 Slump or extensibility: the extensibility of mortar was determined through the mini slump cone technique according to the ASTM C-143 standard (ASTM, 2012).
- 3.3 Compressive strength tests: ASTM C-109 standard, using cubic specimens of 50 mm each side.

3. Results

3.1 Selection and Conditioning of the Raw Material.

Physical properties of the raw material.

Table 2 reports the drying time, moisture and density of the raw material selected and determined at constant temperature. In general, the drying time increased depending on the fineness of each material. The finer the size particle the greater the contact surface area and, therefore, it absorbs more moisture and increases the drying time (De la Garza 2003, Arteaga 2009 and Mondragón 2013).

Tabla 2. Tiempo de secado, porciento de humedad y densidad de la materia prima usada
Table 2. Drying time, moisture percentage, and density of the raw material used

Material	Tiempo de secado/ Drying Time (h)	Humedad/Moisture %	Densidad/Density (g/cm ³)
CPC	6	0.504	3.12
CPC refinado/ <i>Refined CPC</i>	8	1.821	3.12
EGAH gruesa/ <i>Coarse GGBS</i>	6	0.300	2.73
EGAH refinada/ <i>Refined GGBS</i>	7	1.100	2.73
Ceniza volante (CV)/ <i>Fly-ash (FA)</i>	6	0.606	1.85
Humo de sílice (HS)/ <i>Silica Fume (SF)</i>	7	1.107	2.24
Arena de cuarzo/ <i>Quartz Sand</i>	6	0.400	2.63
Microsílice (MS)/ <i>Micro Silica (MS)</i>	6	0.802	2.54

Milling of the ground granulated blast furnace slag (GGBS)

The granulometric analysis of the GGBS as-received presented 80% of the cumulative frequency with sizes of 6000 μ m, considered a coarse size for a HPC component. Therefore, it was reduced to a particle size of less than 150 μ m.

Figure 1 shows the granulometric analysis of fine GGBS, revealing that 80% of the cumulative frequency presents size particles around 150 μ m, which results in higher compressive strength of the products that contain it, compared with coarse GGBS. Due to its fineness, a greater surface area is obtained and, consequently, greater consolidation / densification.

Figura 1. Granulometría de la EGHA fina, en frecuencia acumulada de peso (%)

Figure 1. Grading of fine GGBS, in cumulative frequency of weight (%)

High Energy Milling (HEM)

The optimal milling parameters to achieve the refinement of cement and other minerals in the submicron order were based on previous works (Arteaga 2009 and Mondragón 2013).

Table 3 shows high energy milling parameters of the OPC and GGBS, such as: ball bed filling ratio (J), powder bed filling ratio (f_c) and coefficient of powder/interstices filling (U_R), speed, time and additives.

Tabla 3. Parámetros establecidos para la molienda por alta energía del CPC y EGHA

Table 3. Parameters for high energy milling of CPC and GGBS

Parámetros/Parameters	CPC/OPC	EGHA/GGBS
J	0.54	0.53
f_c	0.11	0.09
U_R	0.7	0.7
Velocidad/Speed	900 rpm	900 rpm
Tiempo/Time	30 min	30 min
Aditivo/Additive	362VW Sika-Graind/SikaGrind	HEA2-21 (Grace)

3.2 Characterization of the milling products.

Chemical Analysis of the Raw Material.

From the chemical analysis of the selected raw material, performed by atomic absorption, a composition with high content of oxides was obtained (CaO , SiO_2 , Al_2O_3 , MgO y Fe_2O_3), being these the main oxides of the Portland cement. Table 4 reports the concentration in weight of the oxides that form the raw material used for the manufacture of HPC.

Tabla 4. Composición química típica de la materia prima
Table 4. Typical chemical composition of the raw material

Material	Compuestos (% peso)/Compound (weight %)				
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO
Cemento CPC	57.60	23.30	06.20	03.20	02.70
Cemento CPC refinado/Refined CPC Cement	49.76	29.32	05.86	03.20	02.43
Escoria (EGAH)/Slag (GGBS)	23.20	29.00	13.00	15.30	07.00
Ceniza volante (CV)/Fly-ash (FA)	02.50	60.00	24.00	06.30	02.00
Humo de sílice (HS)/Silica Fume (SF)	00.30	91.70	01.00	00.80	01.10
Microsílice (MS)/Micro Silica (MS)	00.80	96.30	00.50	02.10	00.30
Arenas de sílice/Silica Sand	00.55	96.60	01.04	00.60	00.35

Scanning Electron Microscopy (SEM).

The morphology of the cementitious particles of HPC compounds was obtained by SEM. Figure 2 shows the difference between the particle sizes of the reference OPC (1) and the refined OPC (2), where the particle agglomeration of the latter is evident due to the cohesive characteristics adopted by the powder when processed by SEM. This agglomeration or aggregation phenomenon of the cementitious particles increases proportionally to the increase of the milling time, because particle agglomeration is induced among surfaces with opposite-sign electric charge.

Figura 2. Micrografía del CPC (1) de referencia y CPC refinado (2), procesado por HEM
Figure 2. Micrograph of the reference OPC (1) and the refined OPC (2), processed by SEM

It should be mentioned that, although pozzolanic materials shown in Figure 3, such as (1) FA, (2) MS and (3) SF, do not have latent cementitious properties like the GGBS, given their fineness and spherical shape; when they come into contact with water they react chemically with calcium hydroxide, derived from the heat liberated during the Portland cement hydration, thereby forming compounds of hydrated calcium silicate (Steven et al., 2004).

Figura 3. Aspecto y tamaño de (1) la CV, (2) MS y (3) HS usados como materiales cementantes para la elaboración del CAD

Figure 3. Appearance and size of (1) FA, (2) MS and (3) SF used as cementitious materials for the manufacture of HPC

The difference between these pozzolanic materials is minimal, since the FA, MS and SF have spherical or globular morphologies; that is, they contain cenospheres (hollow spheres) and plerospheres (spheres that contain spheres in the interior) (Bouzoubaa, 1997 and Fernández et al., 2004). While FA has sizes in the interval of 100-200 μm , MS and SF present sizes of less than 100 μm .

One of the advantages of the existence of spherical shapes in these materials is that it favors the packing of particles inside the HPC, improving the concrete's fluency and workability.

Figura 4. Micrografías de materiales cementantes usados como agregados de (1) EGAH gruesa, (2) EGAH fina y (3) EGAH refinada, en la preparación del CAD

Figure 4. Micrographs of cementitious materials used as aggregates of (1) coarse GGBS, (2) fine GGBS and (3) refined GGBS in the preparation of HPC

The appearance of coarse GGBS particles is shown in Figure 4 (1), it has particle sizes greater than $200\mu\text{m}$ and irregular shapes, which makes packing more difficult in the HPC mixtures.

The fine GGBS shown in Figure 4 (2) was obtained by separating coarse particles by screening, where no symmetrical and defined crystals are observed, but on the contrary, irregular particles with sharp edges are evidenced. This type of morphology is characteristic of slags with potential cementitious properties (Martínez, 2009). Sharp edges of the fine GGBS are due to the type of milling performed during the metallurgical crushing processing (Huiwen, 2004), where particle sizes between 50 and $150\mu\text{m}$ were obtained. The appearance of refined GGBS particles is shown in Figure 4 (3), where irregular geometries are observed with edges that are not so sharp; consequently, some particles present semi-spherical shapes, or at least with rounded edges. Final particle sizes fluctuate between 50 and $150\mu\text{m}$, comparatively with the initial particle size of $>200\mu\text{m}$.

X-ray Diffraction (XRD).

One of the characteristics that defines the hydration speed of Portland cement is the proportion of the amorphous phase and the crystalline state. Therefore, before the hydration of Portland cement, its mineralogical phases were characterized, which determine the final chemical and mechanical properties of the hardened product. The quantitative analysis of the phases begins with the typical mineralogical composition of cement, which varies between: 50-70% Alite, 15-30% Belite, 5-10% Celite and 5-10% Felite. This research monitored exclusively the phases that modified their concentration in a larger proportion during the milling process (HEM), that is, Alite and Belite. These phases are known for their polymorphism (Jadhav et al. 2011). Thus, the Alite phase presented the following states: monoclinic M , triclinic T and rhombohedral R ; while the Belite phase resulted in the beta β and gamma γ states.

Figure 5 shows the XRD patterns of ordinary OPC (as-received) and the OPC processed by HEM. When comparing these results, the peaks of the refined OPC show less intensity while their width tends to increase.

Figura 5. Patrones de difracción de rayos X del polvo de cemento CPC normal y el mismo una vez refinado por HEM
Figure 5. X-ray diffraction patterns of ordinary OPC cement powder and the same once refined by HEM

Considering the fact that some microstructural phases of the cement are more reactive than others (i.e., Alite C_3S is more reactive than Belite C_2 in the first setting hours), and according to surveys carried out by Arteaga (2009) and Fuentes (2014), dry OPC milling by high energy increases the degree of solid-state reaction between the phases of Portland cement. In other words, it is possible to modify the final concentration of the crystalline phases, typically adopted by a clinker at the end of its processing by conventional milling and clinkering methods in the rotating oven, even considering the cooling stage to which it is subjected to. In general, the percentage of the Alite and Belite phases varies depending on the milling conditions, mainly by time and efficiency of the milling or mechano-activation degree. Thus, the Belite phase, which promotes the compressive strength of concrete at long setting times (more than 1 year), precipitates more rapidly with HEM (approx. 1 hour); therefore, the specimens of the present work that contain this fine aggregate show a higher compressive strength in short setting times (1 month).

Figure 5 shows, for example, that the diffraction plane of the ordinary or reference OPC powder, diffracted at approximately 48.5 (2θ) degrees, disappears after milling, as other peaks of lower intensity (Mondragón, 2013). Other changes in the X-ray patterns associated with diffraction planes of Alite and Belite, in the range of 20 to 40 (2θ) degrees, are mainly reported in another work (Fuentes, 2014). This reflects the transformation occurred between the microstructural phases of the cement due to the mechanical action.

Figure 6 shows the diffraction pattern of the fly-ash whose amorphous characteristics are evident from the halo between 15 and 30 (2θ) degrees. This fly-ash, which is rich in silica (SiO_2), is composed of 3 crystalline phases (sillimanite, silica and sodium aluminite).

Figura 6. Patrón de difracción de rayos X del polvo de ceniza volante CV
Figure 6. X-ray diffraction pattern of the fly-ash (FA) powder

The FA diffraction pattern shows that the sodium aluminate and the silica are the predominant phases, the latter being the phase that represents the cementitious property of this material, since it is the compound that provides the concrete's compressive strength.

Furthermore, the GGBS is a silico-aluminous material, which tends to be a highly vitreous material due to the process from which it comes from. Figure 7 shows the GGBS diffraction pattern. An important characteristic is the formation of an amorphous halo in a range of 20 to 40 (2θ) degrees. Weak reflections are observed which correspond to melilite (Sánchez, 2012), which is a typical GGBS phase.

Figura 7. Patrones de difracción de rayos X del polvo de EGAH en tres condiciones; sin moler (tal como se recibió), fina (o tamizada) y refinada (molida por HEM)

Figure 7. X-ray diffraction patterns of GGBS powder in three conditions: without milling (as-received), fine (or as-screened) and refined (as-milled by HEM).

The amorphous halo formed at the base of these diffraction patterns refers to the lime, magnesia, silica and alumina, which coexist and remain in vitreous form after the sudden cooling of the GGBS. Thus, when this material is finely milled, the resulting GGBS develops special pozzolanic and cementitious properties. That is, it adopts a highly reactive chemical behavior.

Figure 8 shows the X-ray diffraction pattern of the silica fume powder, which reveals the existence of an eminently amorphous material, given the silica halo between 15 and 30 (2θ) degrees. CaO_2 and SiC traces are also detected. The presence of compounds with Si, Ca and C is responsible for developing potential cementitious properties in this material and, therefore, it provides high compressive strength to the concrete.

Figura 8. Patrón de difracción de rayos X del polvo humo de sílice HS
Figure 8. X-ray diffraction pattern of silica fume (SF) powder

Figure 9 shows the X-ray diffraction pattern of micro silica (MS), which is also an amorphous material that forms the halo between 15 and 30 (2θ) degrees. In contrast to the silica fume, minor reflection of CaO_2 and Sic are detected here.

Figura 9. Patrón de difracción de rayos X del polvo de micro sílice MS
Figure 9. X-ray diffraction pattern of micro silica (MS) powder

Comparatively, even though the MS presented the same phases as the SF, the first is considered a material with more limited cementitious properties, since in addition to the greater surface area of the fume, the amount of CaO_2 in the MS is smaller. The intensity of the diffraction peaks of the silica in the MS, as well as of the other phases present, is lower compared to the SF.

Thus, the concentration ratio between $\text{SiO}_2/\text{CaO}_2$ is definitely better for the SF and it affects the formation of Alite and Belite, which gives a better compressive strength to the hardened product, through the hydrated calcium silicate (HCS).

3.3 Mixture design.

In addition to the selection and conditioning of materials, the design of the mixture is a very important activity in the HPC manufacturing, because the synergy of intrinsic and extrinsic properties of the base minerals, aggregates and reactant additives has to be achieved. In order to obtain a concrete or mortar with special features, the following characteristics have to be taken into account (Steven, 2004): workability, durability and economy.

Workability: It is understood as the property of the fresh mixture or cement paste to be placed and compacted with proper finishing, in order to prepare concrete and/or mortar. The concrete mixture is said to be workable when it does not produce bleeding (water migration to the surface, thereby provoking sedimentation). In the HPC manufacturing, it is important to point out that there must be a physical-chemical balance between the fineness of the material and the water/additive(s) ratio, which prevents bleeding. Figure 10 shows the behavior of the different HPC mixtures, indicating the basic properties that affect workability, such as: fluency (F), slump (S) and volumetric weight (VW).

Figura 10. Trabajabilidad de las diferentes mezclas desarrolladas para hacer CAD. Relación agua/cemento $w/c = 0.4$
Figure 10. Workability of the different mixtures for making HPC. Water/cement ratio $w/c = 0.4$.

Escalante (2002), Steven (2004) and Sánchez (2009) report that the addition of FA and GGBS generally improves the workability, strength and slump of cement mixtures. They argue that the SF reduces workability, therefore, if used, it is recommended to addition high-range water-reducing additives to keep the workability. This can be clearly appreciated in Figure 10, since the FA and GGBS mixtures (coarse, fine and refined) present higher fluency.

Compressive Strength.

In concretes and mortars, the value of the compressive strength magnitude is one of the parameters that indirectly predicts its durability, which is measured according to the standard in special conditions. Figure 11 was built in order to observe their behavior, and it shows that from the first day of setting until day 28, HPC mixtures evidence high compressive strength tendencies. Nevertheless, although they develop relatively low strength values, mixtures prepared with GGBS exceed the average values of conventional concrete (20 MPa).

Figura 11. Resistencia a compresión de especímenes CAD desarrollada en función del tiempo, para las diversas mezclas analizadas.

Se incluye la curva del CPC de referencia

Figure 11. Compressive strength of HPC specimens based on time, for the different mixtures analyzed. The reference OPC curve is included

Of all OPC mixtures developed in this work, we observe that those with the lowest compressive strength values correspond to GGBS mixtures (coarse, fine and refined). However, it should be mentioned that, in order to achieve its optimal setting and develop high compressive strengths, the GGBS needs an alkaline activator, either Na_2SiO_3 , $\text{Ca}(\text{OH})_2$ or NaOH (Escalante, 2002 and Sánchez, 2012), a product that was not used in this work.

According to the results, the cementitious material which developed the highest compressive strength values, and with acceptable workability, was the SF (Figure 11), probably because its chemical composition has high silica contents (90% SiO_2) and a greater proportion of CaO_2 than the MS, an extremely fine unimodal particle size and a fluency that turns it into a self-compacting cementitious material.

In other words, this type of cementitious composites developed a high volumetric density with the setting time, in contrast to other specimens. The SF contributes to the filling of interstices in the mixture, thereby increasing the density and reducing the permeability of the final product; so, this mixture is less porous. Consequently, its mechanical and durability properties improve. Other equally important factors that contribute to obtain high compressive strengths in this type of developed HPC, are the transformation reactions between the Alite C_3S and Belite C_2S phases, which were induced during the HEM processing, as well as the size and spherical shape of the particles, which favor this characteristic in the short and long curing terms.

4. Conclusions

The present study analyzed the benefit of incorporating different fine mineral aggregates conditioned by high energy milling (HEM) to an optimized OPC mixture (ordinary and refined), in order to develop high-performing concrete (HPC) with Mexican mineral resources.

The advantage of using HEM in the manufacture of HPC is that it increases the Belite C_2S phases at the expense of the Alite C_3S phases in the composite Portland cement (OPC) after 30 min of milling; the Belite phase seems to provide higher strength to the concrete specimens in the short and long run.

OPC mixtures enriched with different fine mineral aggregates, which contain silica fume, showed the highest compressive strength values, and are recommended for the manufacture of a type of HPC.

The GGBS presents low compressive strength in spite of its high content of amorphous phase and the particle size refinement to which it was subjected to, since it requires a post alkaline activation for developing better cementitious properties.

In order to obtain high performing concrete (HPC) that exceeds the compressive strength of conventional concrete, a cementitious material with particle sizes less than $0.5\mu m$ is required, with spherical morphology, high contents of SiO_2 , addition of ordinary OPC with a proportion of 30% of refined OPC, the use of water-reducing additives, and a w/c ratio not higher than 0.4. This was found to be the case for the silica fume (SF) mixture, which was used as cementitious material.

5. Acknowledgements

The authors wish to thank the CIITEC-IPN through the SIP-IPN project, Nr 20131294, for their support in the preparation of the present study; AHMSA companies, Sika Mexicana S.A. de C.V., and Grace Construction Products for sharing their laboratories in order to conclude this survey. MTFR thanks CONACyT and IPN for the scholarship granted to the achievement of their doctoral studies.

6. Referencias/References

- Arteaga J.C. (2009)**, "Comportamiento mecánico y caracterización de morteros elaborados con cemento Portland ultrafino", Tesis doctoral, CICATA-IPN, México.
- Bouzoubaa N., Zhang M. H., Bilodeau A., Malhotra V.M. (1997)**, "The effect of grinding on the physical properties of fly ashes and Portland cement clinker", Cement and concrete research V.27 (12) pp. 1861-1874.
- De la Garza Hernán (2003)**, "Cemento portland ultra-fino de alta resistencia", Tesis maestría, CIMAV, México.
- Escalante J. I. (2002)**, "Materiales alternativos de cemento Portland", Avance y perspectiva, Vol.21, 2002, pp.79-88.
- Fernández J. A., Palomo A., Criado M. (2005)**, "Microstructure development of alkali-activated fly ash cement descriptive model", Cement and concrete research V.35 (6) pp. 1204-1209.
- Fuentes M. T. (2014)**, "Efecto del tamaño de partícula y agregados finos en la preparación de un tipo de concreto de polvo reactivo CPR", Tesis Doctoral, CIITEC-IPN, México.
- Huiwen W., Zhonghe S., Zongshou L. (2004)**, "Analysis of geometric characteristics of GGBS particle and their influences of cement properties", Cement and concrete research V.34 (1) pp. 133-137.
- Jadhav R. y Debnath N. C. (2011)**, "Computation of X-ray powder diffractograms of cement components and its application to phase analysis and hydration performance of OPC cement" Bull. Mater. Sci., Vol. 34, No. 5, pp. 1137-1150.
- Lorenzo Ma. P. (1993)**, "Influencia de dos tipos de cenizas volantes españolas en la microestructura y durabilidad de la pasta de cemento Portland hidratado", Tesis doctorado, Universidad Complutense de Madrid, España.
- Martínez M. J. (2009)**, "Estudio de la hidratación de la escoria granulada de alto horno (EGAH) a diferentes temperaturas", Tesis Maestría, ESIQIE, México.
- Martínez R. (2011)** "Apuntes de concreto de alto desempeño", Ingeniería civil, Universidad Autónoma de Nuevo León, México.
- Pierre A., (1998) "High Performance Concrete" Ed. E & FN Spon Press.
- Mondragón M. (2013)**, "Efecto de aditivos químicos en la resistencia a la compresión del concreto de polvo reactivo (CPR)", Tesis maestría, CIITEC, México.
- Norma Americana ASTM – C138 9 (2012)**, Método de Ensayo Normalizado de Densidad (Peso Unitario), Rendimiento, y Contenido de Aire (Gravimétrico) del Concreto.
- Norma Americana ASTM – C143 (2012)**, Método de Ensayo Normalizado para Asentamiento de Concreto de Cemento Hidráulico.
- Norma Americana ASTM – C109(2012)**, Método Normalizado de Ensayo de Resistencia a Compresión de Morteros de Cemento Hidráulico (Utilizando especímenes cúbicos de 2 pulgadas o [50 mm]).
- Regoud M. (1980)**, "Structure and behavior of slag Portland hydrates", Microestructure Department C.E.R.I.L.H., 7th International Congress on the Chemistry of cement.
- Rivva E. (2000)**, "Naturaleza y Materiales del Concreto", II Congreso Nacional de Estructuras y Construcción, Capítulo Peruano del ACI, Capítulo 2 pp. 21-25.
- Sánchez R. (2012)**, "Desarrollo y caracterización de compósitos cementantes con reemplazo de escoria de alto horno para la industria petrolera", Tesis Doctoral, ESIQIE-IPN, México.
- Steven H. Beatrix K, Panarese W, Tanesi J. (2004)**, "Diseño y Control de Mezclas de Concreto", Portland Cement Association, 1ª Ed., Capítulo 5, pp. 72-73. Capítulo 7 pp.83-95.
- Valdez. P L., Alejandro D., Jorge M. R., César A. J., (2007)**, "Concretos fluidos con altos volúmenes de ceniza volante", Universidad Autónoma de Nuevo León, México.