



## Fly ash effect on mechanical properties of concretes made with high absorbent crushed limestone aggregates

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### ABSTRACT

Concrete made with high-absorbent crushed limestone aggregates from Yucatán, México are well known as a low quality concrete. The aim of this investigation is to enhance the mechanical properties of concrete with high absorbent crushed limestone aggregates and fly ash. The measured properties were: compressive strength and elastic modulus. The water/cement ratios were 0.5 and 0.7, fly ash was incorporated as partial substitution of cement with 20% and 40% and as a mineral additive in 10% and 20%. Results show that fly ash can be used in this kind of concretes as mineral additive due to compressive strength was similar to those reference samples. Finally, an equation for predicting mechanical properties is reported.

**Keywords:** fly ash, limestone aggregates, absorption, compressive strength, elastic modulus.

### RESUMEN

El concreto elaborado con agregado calizo triturado de alta absorción de Yucatán, México, es considerado de baja calidad. El objetivo de la investigación es mejorar las propiedades mecánicas del concreto elaborado con este tipo de agregado incorporando ceniza volante (CV). Las propiedades medidas fueron: Resistencia a la compresión (RC) y módulo de elasticidad. Se utilizaron relaciones agua/cemento de 0.5 y 0.7, la CV se incorporó como sustitución parcial del cemento en un 20% y 40%, y como aditivo mineral en un 10% y 20%. Los resultados indican que la CV puede ser utilizada en concretos con ACTAA como agregado inerte fino ya que logra mantener una RC similar a la referencia. Se presentan ecuaciones para la predicción de propiedades mecánicas.

**Palabras clave:** ceniza volante, agregado calizo, absorción, resistencia a la compresión, módulo de elasticidad.

### RESUMO

O concreto feito com esmagado limestone agregada alta absorção de Yucatan, no México, é considerado de baixa qualidade. O objectivo da investigação é o de melhorar as propriedades mecánicas do betão fabricado com este tipo de cinzas incorporando mosca agregado (CV). As propriedades medidas foram: resistência à compressão (RC) e módulo de elasticidade. Foram utilizadas razões água / cimento de 0,5 e 0,7, o CV foi incorporado como substituição parcial de cimento de 20% e 40%, e como um aditivo mineral a 10% e 20%. Os resultados indicam que o CV pode ser usado em concreto com ACTAA inerte adicionada tão fina quanto possível manter um RC de referência semelhantes. Equações para predizer propriedades mecánicas são apresentados.

**Palavras chave:** cinzas volantes, agregados de calcário, absorção, resistência à compressão, módulo de elasticidade.

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## 1. INTRODUCTION

Commonly, aggregates in concrete are two-thirds of the total volume and can influence in high grades the workability, mechanical properties, durability and porosity. In addition, they had used to reduce costs and provide stability. Therefore, aggregates characterization is essential to design and predict concrete behavior.

Concrete from Yucatán Península is made with crushed limestone aggregates with higher absorption, porosity, fineness powders, fragility and lower density. These properties are proper of deficient aggregates compared with lower absorption aggregates (Moreno and Arjona, 2011). Hence, the aggregate phase has influence in the mechanical properties of the concrete as Compressive Strength (CS) and Elastic Modulus (EM) and trigger an increase the cement amount to achieve target mechanical properties. Given these conditions, Solís and Moreno (2012) investigated the maximum CS in concretes with High Absorptions Crushed Limestone Agreggates (HACLA) and a w/c ratio between 0.20 and 0.45. The volume of cement was from 460 to 1300 kg/m<sup>3</sup> without pozzolans. The maximum CS was around 500 kg/cm<sup>2</sup> at 28 days and 600 kg/cm<sup>2</sup> at later ages. There was not a significant increase in CS with higher volumes of cement such as 850 kg/m<sup>3</sup> because the aggregates strength was exceeded. Cement is the most expensive material both economically and environmentally in concrete, therefore supplementary cementitious materials could be considered as a requeriment in any construction. Pozzolans are siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (ASTM C 125). Therefore, pozzolans are used to Portland Cement substitutions or as mineral admixtures to achieve similar or higher mechanical properties in Portland Cement based concretes.

Pozzolans are not commonly used in Yucatan Peninsula due to the lack of volcanic activity near from the región and industry development without puzzolanic residues. However, Aportela and Pardo L. (2002) studied the technical feasibility to use natural fly ash from Popocatepetl volcano as a supplementary cementitious materials in concrete with HACLA, authors observed a decrease in Compressive Strenght when this fly ash was added to concrete.

At Nava, México region, a significant amount of Fly Ash (FA) is obtained from a carboelectric factory due to pulverized carbon burn. This FA is classified as an artificial type F due to the origin and oxide composition according to ASTM C 618. It has been reported concrete with high compressive strength due to high contents of FA from Nava region and with low content of Portland Cement (100-150 kg/m<sup>3</sup>), and the use of superplasticizer is a key to achieve the flowability (Valdez P. et al. 2007). Pozzolanic Activity was not investigated in Valdez P. work; However, if compressive strength increases, elastic modulus should increase too, therefore, FA from Nava was consider as a material with potential in concrete industry at México.

Siddique R. (2003) investigated mechanical properties of concrete (CS and EM) with fly ash mineral additions in 10%, 20%, 30%, 40% y 50%; higher values were obtained from the mixtures with mineral additions compared to the reference, also it was conclude that FA class F can be use for structural porpuses.

Porositys registered in concrete with HACLA oscilate between 18% and 25% for different water/cement ratios, this value is higher than concretes made with another kind of aggregates. A decrease of the porosity in cement paste phase with FA from Nava region is propose as a solution to enhance mechanical properties on concrete with HACLA.

The main objective from this work is to determine the performance of FA to decrease porosity and enhance mechanical properties such as Compressive Strength and Elastic Modulus in concrete with HACLA. Another focus is to optimize the amount of cement paste when is partially substituted by FA. However, from social perspective, the use of an industrial waste as fly ash also has an important impact in the region where is produced.

## 2. EXPERIMENTAL PROCEDURE

Materials used to cast concrete mixtures were characterized according to American Society of Testing Materials (ASTM) standards. Composite Portland Cement (CPC 30R) was used in the cast of specimens due to his often use at Yucatán Peninsula and the materials for this project has to be the closest possible to the construction field. This cement satisfy the requirements from NMX C-414 ONNCCE norm.

Morphology from FA was performed with an Image Analysis through Scanning Electronic Microscope (SEM), oxide composition was calculated by X-ray fluorescence (FRX), Particle Size Distribution was performed by Laser diffraction; also, Pozzolanic Activity Index (PAI) and Density were measured.

Mixture proportions were calculated according to American Concrete Institute Code (ACI 211.1) with two modifications:

1. Absorption of coarse and fine aggregates was considered as the 70% of the calculated absorption according to ASTM C127/C128 standards because of saturation on aggregate samples were during 15 and 60 minutes instead of 24 hours after being dried in the furnace at 100°C for 24 hours (Hernández, 2013)
2. Fly ash addition as a supplementary cementitious material (Mixtures SCV-20 and SCV-40, table 1) and as mineral admixture (Mixtures ACV-10 and ACV-20). When fly ash was added, fine aggregate was replaced in mixtures.

Ten mixtures were designed with water/binder (w/b) ratio of 0.5 and 0.7. At Table 1, nomenclature of mixtures is given to practical reading purposes. Each mixture was of 55 liters and the numbers of specimens are presented at table 2. The specimens were cast according to ASTM C 31 and were cured with lime water.

Table 1. Concrete mixtures nomenclature.

Name	Mixture number	Characteristics
MR	2	Reference
SCV-20	2	20% substitution of cement by FA
SCV-40	2	40% substitution of cement by FA
ACV-10	2	10% mineral addition of FA
ACV-20	2	20% mineral addition of FA

Table 2. Concrete specimens

Compressive strength at 28 days	Compressive Strength at 91 days	Elastic Modulus	Porosity, density and absorption
4 specimens of 10 cm per 20 cm	4 specimens of 10 cm per 20 cm	4 specimens of 15 cm per 30 cm	4 specimens of 7.5 cm per 10 cm

Compressive Strength, Elastic Modulus and porosity measurements were determined according to ASTM standards.

### 3. RESULTS

Physical characterization of fine and coarse aggregates such as unit weight, specific gravity, absorption, abrasive resistance and fineness modulus are given at table 3. Presented values are the average of 3 samples. Particle size distribution of fine and coarse aggregates are presented at figures 1 and 2. It's observed that coarse aggregates do not satisfy ASTM C33 especifications in contradistinction to fine aggregates.

Tabla 3. Aggregates properties

Type	Specific gravity (SSS)	Loose Unit weight (kg/m <sup>3</sup> )	Compact Unit weight (kg/m <sup>3</sup> )	Absorción (%)	Abrasion (%)	Fineness modulus
Grueso	2.32	1113.41	1234.40	8.1	32	-----
Fino	2.42	1280.36	-----	6.8	-----	2.72

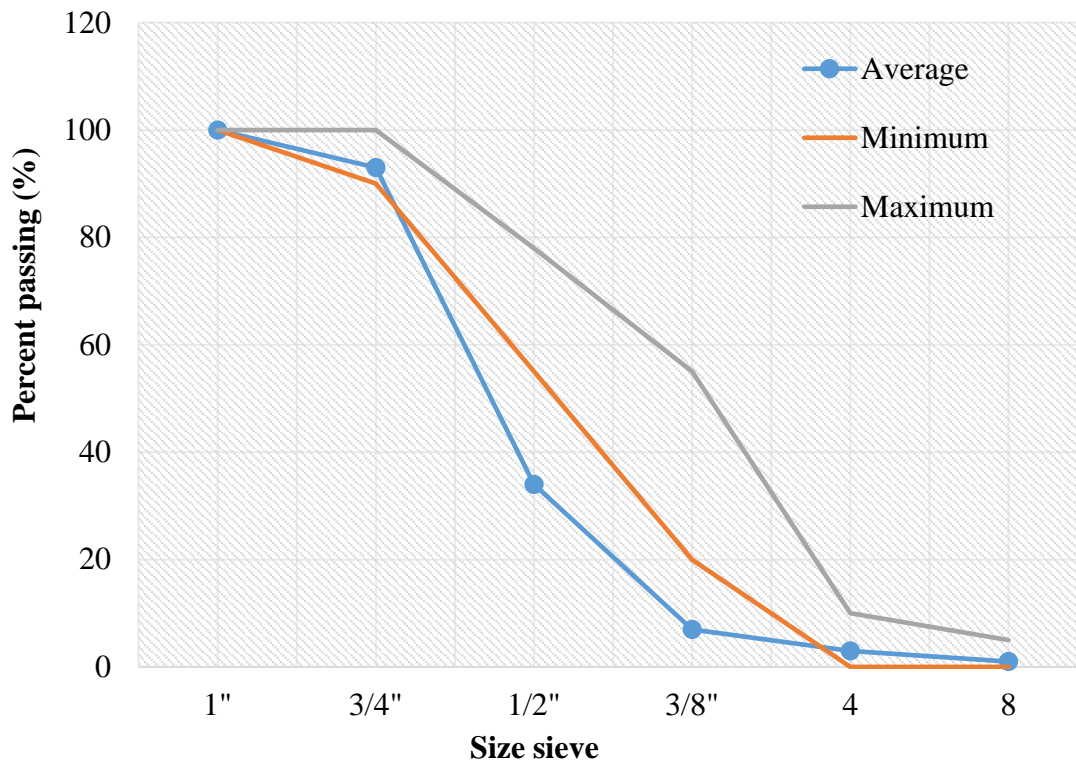


Figure 1. Particle Size Distribution of Coarse Aggregates.

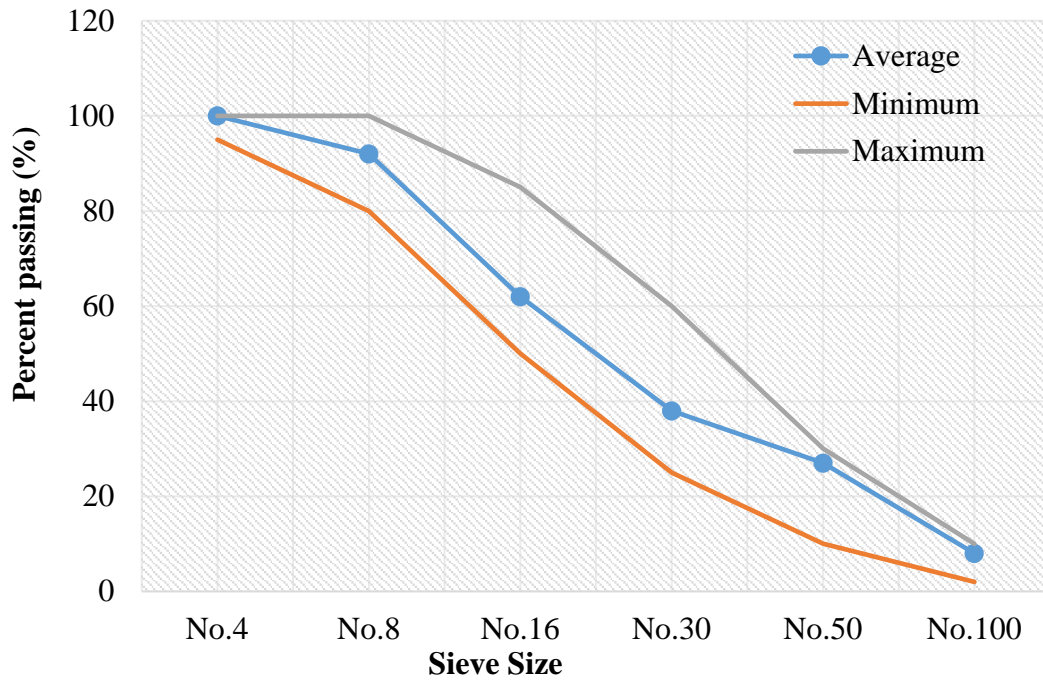


Figure 2. Particle Size Distribution of fine aggregates

Fly ash should satisfy certain oxide composition, fineness and a Pozzolanic Activity Index to use within concrete according to ASTM C618. Total Oxide amount of aluminium, silica and iron should be as minimum 70% (table 4). Density of fly ash was 2.0 g/cm<sup>3</sup> according to ASTM C 311 and C188 method.

Table 4. Fly Ash oxide composition

Compound	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>		SiO <sub>2</sub>	SO <sub>3</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>
Percent (%)	3.315	1.667	33.105		56.511	0.344	0.518	0.698	0.357	1.486

Particle size distribution of fly ash was determine through difraction laser with a MICROTRAC equipment (figure 3). According to ASTM C 618, fly ash shouldn't retain more than 35% of his total weight through sieve no. 325 of 45 micrometers.

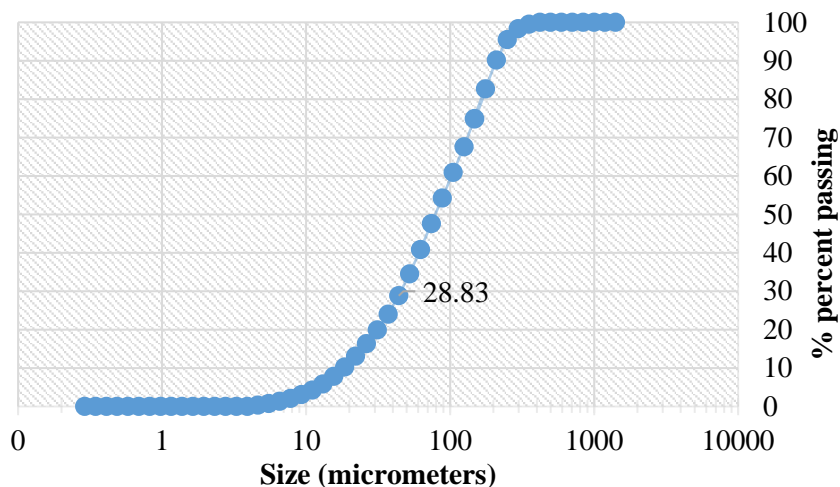


Figure 3. Particle Size Distribution.

Finally, according to ASTM C 618, fly ash should obtain a PAI minimum of 75% at 7 or 28 days to be considered as a pozzolan in concrete. Results are given at table 5.

Table 5. Pozzolanic Activity Index results.

Nom	Age	Compressive Strength (Kg/cm <sup>2</sup> )	PAI (%)
MR-7	7 days	327.3	75%
MCV-7	7 days	244.6	
MR-28	28 days	401.5	82%
MCV-28	28 days	328.9	

Scanning Electronic Microscope images were taken at 1000 and 10000 x (Figure 4).

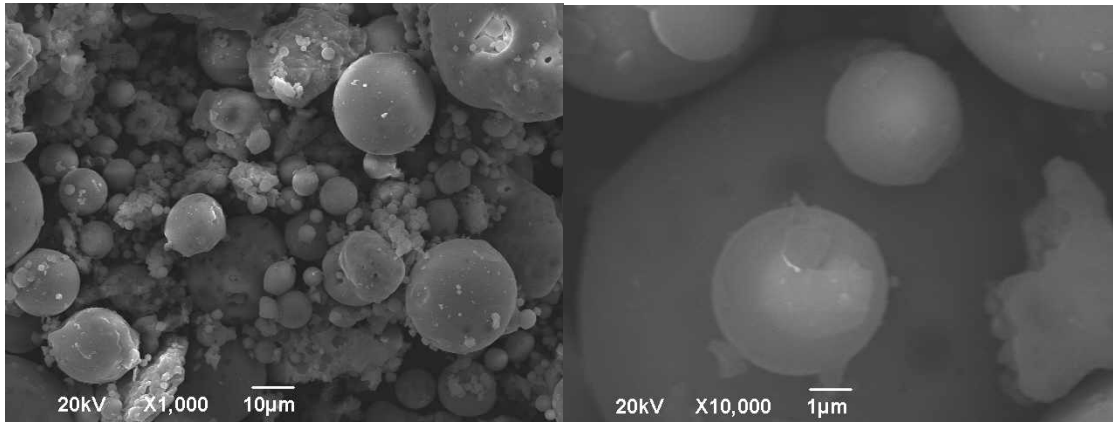


Figure 4. Fly ash images taken with SEM

Mixtures design are given at table 6 with aggregates in a saturated condition. Results in CS tests at 28 and 91 days, EM at 28 and 91 days and porosity at 91 days are given at table 7, 8 and 9 correspondely.

Table 6. Mixtures design

	SCV-40	SCV-20	MR	ACV-10	ACV-20	SCV-40	SCV-20	MR	ACV-10	ACV-20
w/b	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.7
water (Kg/m <sup>3</sup> )	200.9	202.9	205	204	202.9	202.1	203.5	205	204.3	203.5
Cement (kg/m <sup>3</sup> )	241.1	324.7	410	407.9	405.9	173.2	232.6	292.9	291.8	290.8
FA (kg/m <sup>3</sup> )	160.7	81.2	0	40.8	81.2	115.5	58.2	0	29.2	58.2
Coarse aggregates (kg/m <sup>3</sup> )	823.7	832	840.4	836.1	832	828.4	834.3	840.4	837.4	834.3
Fine aggregates (kg/m <sup>3</sup> )	646.4	665	683.9	643.1	602.6	745.7	759.7	773.9	744.4	715
Slump (mm)	30	50	30	50	40	60	100	30	160	140
Air (%)	4.2	3.8	3.9	4	3.9	4.3	4.1	4.2	4	4.1
Unit weight (kg/m <sup>3</sup> )	2086	2124	2180	2145	2125	2071	2100	2143	2120	2114

Table 7. Compressive Strenght results

Mixture	w/b	Average strenght (kg/cm <sup>2</sup> )	Standard deviation (kg/cm <sup>2</sup> )	Variation coefficient (%)	Average strenght (kg/cm <sup>2</sup> )	Standard deviation (kg/cm <sup>2</sup> )	Variation coefficient (%)
		28 days			91 days		
SCV-40	0.5	232.9	8.1	3	272.9	17.1	6
SCV-20	0.5	300.0	17.0	6	328.4	31.3	10
MR	0.5	329.5	12.7	4	360.6	17.1	5
ACV-10	0.5	335.3	9.9	3	358.9	17.0	5
ACV-20	0.5	328.2	5.4	2	356.7	13.9	4
SCV-40	0.7	145.9	7	5	182.6	15.1	8
SCV-20	0.7	206.3	12.8	6	241.5	15.2	6
MR	0.7	275.1	7.2	3	295.6	10.6	4
ACV-10	0.7	241.1	5.5	2	285.0	7.0	2
ACV-20	0.7	228.2	3.0	1	283.1	2.3	1

Table 8. Elastic Modulus results.

Mixtures	w/b	f'c (kg/cm <sup>2</sup> )	Average EM (kg/cm <sup>2</sup> )	Standard Deviation (kg/cm <sup>2</sup> )	Variation Coefficient (%)
SCV-40	0.5	232,9	200544,4	11136.7	6
SCV-20	0.5	300,0	218886,6	11208.6	5
MR	0.5	329,5	234237,5	32788.9	14
ACV-10	0.5	335,3	241605,9	12205.2	5
ACV-20	0.5	328,2	235716,8	3842.9	2
SCV-40	0.7	145,9	157068,7	3886.7	2
SCV-20	0.7	206,3	189455,2	4494.7	2
MR	0.7	275,1	215601,9	11315.6	5
ACV-10	0.7	241,1	210051,6	7107.6	3
ACV-20	0.7	228,2	201662,4	8718.5	4

Tabla 9. Porosity in concrete at 91 days results.

Mixture	w/b	Age (days)	Average Porosity (%)	Standard Deviation (%)	Variation Coefficient (%)
SCV-40	0.5	91	24.3	0.56	2
SCV-20	0.5	91	22.0	0.13	1
MR	0.5	91	21.5	0.46	2
ACV-10	0.5	91	22.9	0.55	2
ACV-20	0.5	91	23.1	0.59	3
SCV-40	0.7	91	25.3	0.2	1
SCV-20	0.7	91	23.5	0.22	1
MR	0.7	91	21.8	0.68	3
ACV-10	0.7	91	23.9	0.30	1
ACV-20	0.7	91	23.1	0.49	2

#### 4. DISCUSSION

Coarse aggregates did not satisfy with the particle size distribution recommended by ASTM C 33. It has insufficient amount of 3/8" aggregate size due to a lack supervision on the grinding process. Absorption value of coarse aggregates is high due to his porosity and low density. Fine aggregate satisfied with ASTM C 33 requirements. According with the Fineness Module, it is classified as a medium sand. However, the absorption and density are similar to coarse aggregate values. Fly ash satisfied the oxide composition with a 91.1% value, therefore is classified as a FA class C; also obtained a PAI of 75% at 7

days and 82% at 28 days according to ASTM C 618. Density of FA is lower than cement and aggregates; however, the measured value is within regular values as Neville mentioned at 1998. However, FA does not satisfied the fineness requirement to be considered as a Pozzolan within concrete because only 28.83% has the minimum particle size; however, grinding was not considered due to the main objective of use FA directly from the source and observe mechanical properties influence. When Fly ash is added as a mineral addition, a volume percent of fine aggregate is substituted. According to ASTM C 33, fly ash will increase the fineness amount in the concrete considering FA as a fine aggregate, however the fineness of FA proportioned an increase on packing within concrete. Image analysis from SEM (figure 4) confirm the spherical shape particle of FA.

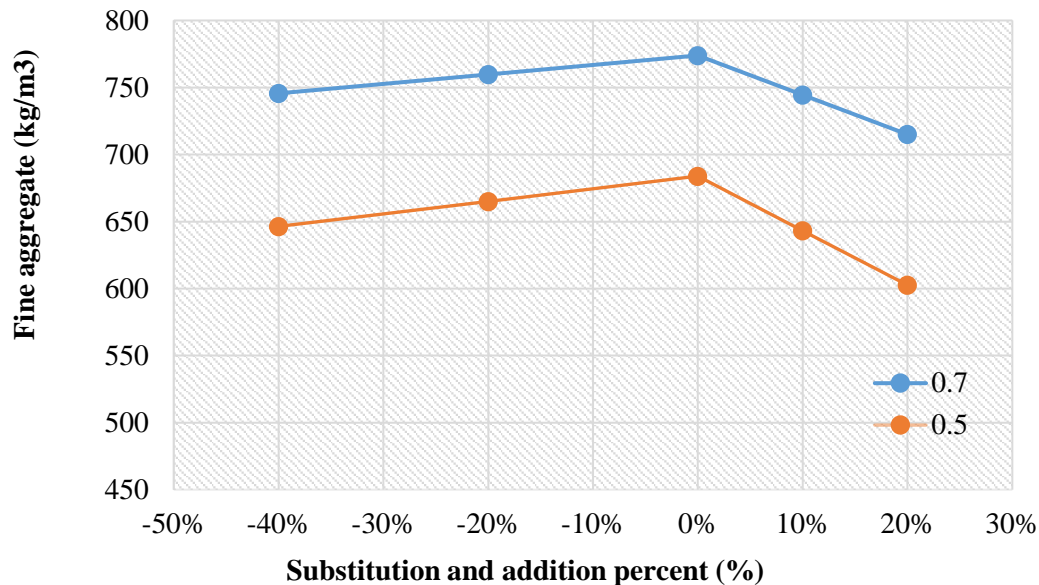


Figure 5. Fine aggregate variation

Volume of fine aggregate in mixtures decreased with fly ash addition both addition and substitution of portland cement (figure 5) due to a difference of densities between fly ash and portland cement. Fly ash occupies more volume than portland cement when this was substituted in mixtures. Therefore, an increase on cementitious volume paste and a decrease on fine aggregate volume result in raw materials saving.

Compressive Strength on concrete specimens with w/b of 0.5, mixture ACV-10 reached a CS higher than 334.4 kg/cm<sup>2</sup> (value recommended at ACI 211.1 at 28 days, no more mixtures reached the target CS. In concrete specimens of 91 years age, mixtures MR, ACV-10 and ACV-20 obtained higher CS than values recommended from ACI, however, mixtures ACV-10 and ACV-20 obtained less CS than the reference MR.

Compressive strength on all concrete specimens with w/b of 0.7 (except SCV-40) obtained a higher value than target value from ACI 211.1 of 200 kg/cm<sup>2</sup> at 28 and 91 days age. Fly ash did not improve the CS in any mixture either substitution or mineral addition compared with reference mixture, therefore, the increase on compressive strength from 28 days to 91 days is due to cement. A correlation between w/b ratio, substitution/addition percent of cement by fly ash and concrete age was made through a variance analysis (ANOVA) to predict compressive strength of concrete (table 10). The independent variables were concrete age, real w/c ratio, volume relation of FA and total volume of mixture and dependet variable was compressive strength as is shown in Table 10. Through a multiple regression in ANOVA programa equation 1 was obtained.



$$f'c = (0.54) * (age) - 291.21 * (w/c) + 312.12 * \left( \text{Vol. F.A.} / m^3 \right) + 447.5 \quad (1)$$

Where:  $f'c$  = CS in kg/cm<sup>2</sup>, Age= Concrete age in days, w/c = real w/c ratio, Vol. F.A./m<sup>3</sup> = Relation of FA volume per m<sup>3</sup>.

Table 10. Relation between concrete age, w/b ratio, real w/c, real FA volumen/total mixture volumen and compressive strenght

Mixture	w/b	Age (days)	w/c real	Vol F.A./total vol	CS (kg/cm <sup>2</sup> )	Calculated CS (kg/cm <sup>2</sup> )	Erro percent (%)
SCV-40	0.5	28	0,8	0.05	232.9	236.3	-1%
SCV-20	0.5	28	0,6	0.03	300.0	288.9	4%
MR	0.5	28	0,5	0	329.5	317.1	4%
ACV-10	0.5	28	0,5	0.01	335.3	321.2	4%
ACV-20	0.5	28	0,5	0.03	328.2	325.3	1%
SCV-40	0.5	91	0,8	0.05	272.9	270.6	1%
SCV-20	0.5	91	0,6	0.03	328.4	323.1	2%
MR	0.5	91	0,5	0	360.6	351.4	3%
ACV-10	0.5	91	0,5	0.01	358.9	355.5	1%
ACV-20	0.5	91	0,5	0.03	356.7	359.5	-1%
SCV-40	0.7	28	1,2	0.04	145.9	134.6	8%
SCV-20	0.7	28	0,9	0.02	206.3	213.7	-4%
MR	0.7	28	0,7	0	275.1	258.9	6%
ACV-10	0.7	28	0,7	0.01	241.1	261.8	-9%
ACV-20	0.7	28	0,7	0.02	228.2	264.7	-16%
SCV-40	0.7	91	1,2	0.04	182.6	168.9	8%
SCV-20	0.7	91	0,9	0.02	241.5	248.0	-3%
MR	0.7	91	0,7	0	295.6	293.2	1%
ACV-10	0.7	91	0,7	0.01	285.0	296.1	-4%
ACV-20	0.7	91	0,7	0.02	283.1	299.0	-5%

Considerations to use equation 1 are given in the following order:

- Concrete has to be made with CPC 30R and Class F Fly ash
- Curing regime of concrete should be with limewater for up to 28 days.
- High absorption Crushed limestone Aggregates with nominal diameter of ¾" should be used.
- Concrete design should be made according to ACI 211 recommendations with the changes explained in "experimental details chapter" and concrete design to achieve a target slump between 7.5 and 10cm.

Elastic Modulus of each mixture were calculated according to Complementary Technical Standards of Norms Construcion from Federal District (NTC RDF spanish acronym) equations for class 2 concrete and volumetric weight lower than 2200 kg/m<sup>3</sup> (equation 2), ACI 318 standard equations for concrete with unit weight between 1440 kg/ m<sup>3</sup> and 2480 kg/m<sup>3</sup> (equation 3) and equations from Facultad de Ingeniería of Universidad Autónoma de Yucatán (FIUADY) research made by Hernández at 2013, where a relation between aggregates density and square root of compressive strength was established to predict Elastic Modulus in concretes with HACLA (equation 4). Comparision of results are given in table 11.

$$E = 8000 * \sqrt{f'c} \quad (2)$$

$$E = W_c^{1.5} x 0.14 \sqrt{f'c} \quad (3)$$

$$E = 2273.69 \times GEAF \times GEAG \times \sqrt{f'c} \quad (4)$$

Where: E= EM en kg/cm<sup>2</sup>, Wc= Unit weight of concrete in kg/m<sup>3</sup>, f'c= CS in kg/cm<sup>2</sup>, GEAG = Specific gravity of coarse aggregate (SSS), GEAF = Specific gravity of fine aggregate (SSS), f'c (kg/cm<sup>2</sup>)= CS.

Table 11. Comparison between obtained data and models to determine EM

Mixture	w/b	f'c <sup>1/2</sup>	EM obtained (kg/cm <sup>2</sup> )	EM (NTC RCDF)	EM (Hernández 2013)	EM (ACI 318)
SCV-40	0.5	15,26	200544,4	122085,9	194809,4	201300,4
SCV-20	0.5	17,32	218886,6	138561,8	221099,6	237284,3
MR	0.5	18,15	234237,5	145219,3	231722,9	258740,1
ACV-10	0.5	18,31	241605,9	146485,2	233742,9	254684,9
ACV-20	0.5	18,12	235716,8	144936,9	231272,4	248545,4
SCV-40	0.7	12,08	157068,7	96627,9	154186,9	161137,5
SCV-20	0.7	14,36	189455,2	114902,4	183346,9	193506,7
MR	0.7	16,59	215601,9	132691,5	211732,6	230386,5
ACV-10	0.7	15,53	210051,6	124211,4	198201,2	212120,9
ACV-20	0.7	15,11	201662,4	120860,9	192854,8	205540,9
Difference between obtained EM and models to determine EM.				>39%	>2%	<5%

Correlation between obtained and calculated results with NTC-RCDF equations was made by calculating K function of Elastic Modulus obtained in experimental work with a lineal regression in Microsoft Excel. Consideration as f'c= 0 was taken to obtained a EM of 0 (figure 6). This is shown in equation 5.

$$E = 13079 \sqrt{f'c} \quad (5)$$

Where: E= ME in kg/cm<sup>2</sup>, f'c= RC in kg/cm<sup>2</sup>. Obtained equation has a K of 60% up than NTC RDF standards. Consequently, the use of NTC RDF equations allow overstating concrete structures design, then, regional standards should be done according to aggregates type.

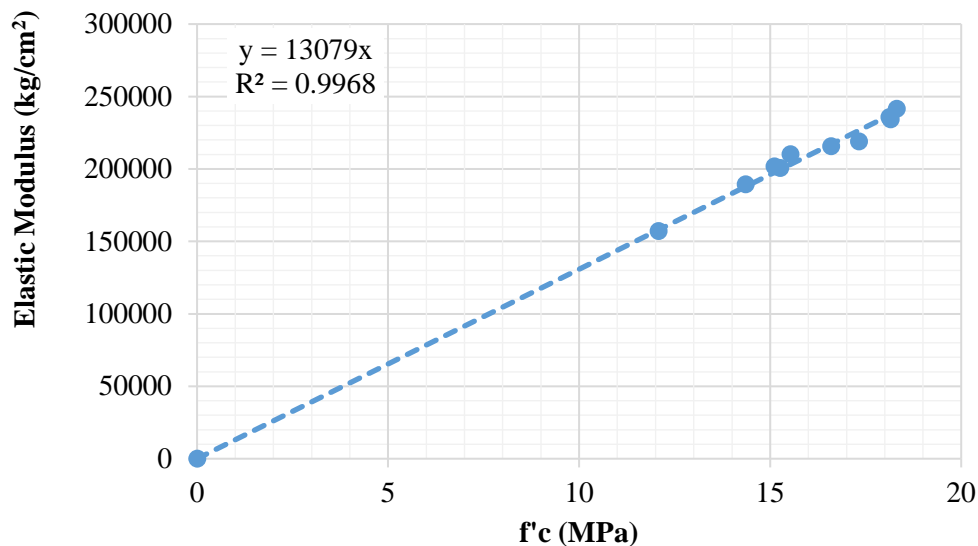


Figure 6. Lineal regression of results

Fly ash did not have a significant influence in Porosity, density and absorption results. However, it was observed a small increase of porosity when fly ash was added (Table 9).

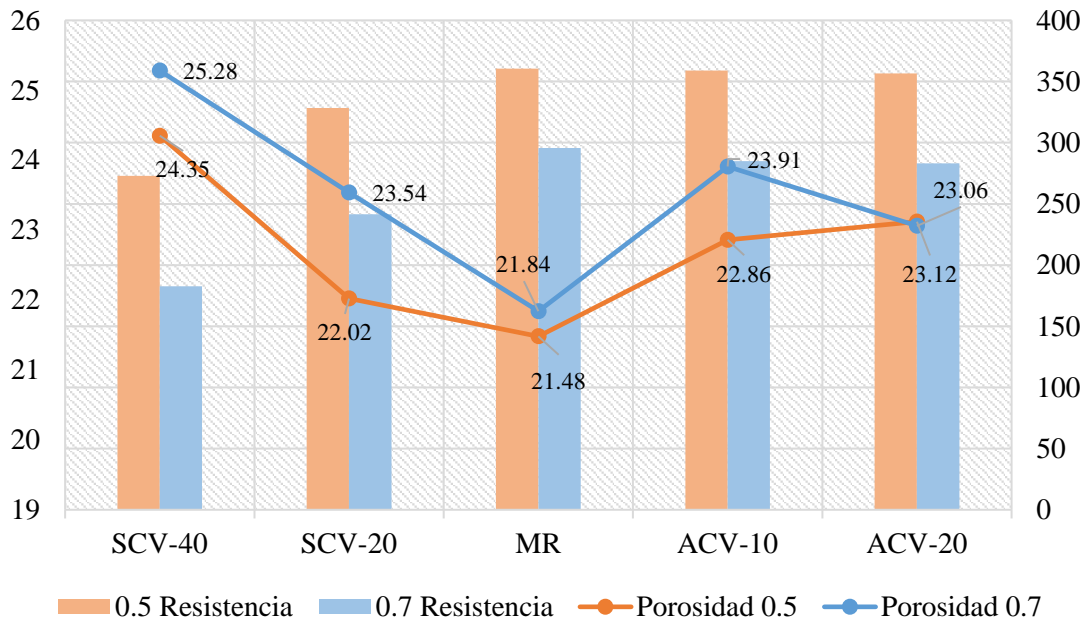


Figure 7. Porosity and Compressive Strength

Porosity is a main factor in mechanical properties and durability in concrete, the higher porosity is lower mechanical properties are obtained, resulting in a lack of durability performance in aggressive environments (Mehta & Monteiro, 1998). It was observed a tendency on compressive strength decrease when porosity increases (figure 7) taking MR mixtures as a reference. However, porosity percents have a low variation range of +/- 4%. Only mixtures of cement substitution by Fly Ash obtained a significant decrease in compressive strength when porosity increases compared with MR mixtures. Experimental work from Solís and Moreno, 2011 concluded that porosity criteria in concrete with HACLA is not adequate to determine the quality of concrete. Relation between CS and Porosity results in this work seems to corroborate Solís & Moreno conclusions.

## 5. CONCLUSIONS

Class F Fly Ash from Nava, México is recommended to use in concrete with HACLA as an inert fine aggregate due to the following arguments:

- Even if compressive strength was not increased by fly ash this remained
- Fly ash concrete employment allows a usefulness to this material currently destined to environment affecting nearby urban zones.

According to mechanical properties results, the following conclusions were established:

- A lack of Pozzolanic Activity from Fly ash was obtained, even when certain requirements were satisfied; fly ash was not able to enhance quality in concrete with HACLA. However, fly ash can be used adjusting mixtures design with equation 1 and 5 to maintain target CS and EM, even without modifications to fly ash such as grinding.
- Equations 1 and 2 to determine CS and EM for concretes with HACLA were calculated to avoid overstating in concrete structures from Yucatán and optimize the raw materials.

Fineness of fly ash should be increase by grinding to enhance the pozzolanic activity and packing in concrete.

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