

# Aggregate particle size interrelations and case study in concrete using white ordinary Portland cement

## Interrelaciones de tamaño de partículas de agregados y su estudio en el caso concreto utilizando cemento Portland blanco ordinario

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### Abstract

The size distribution, the gradation and the type of aggregates are factors of great relevance for the design of mixtures in concrete and construction materials in general since these allow us to obtain information on the voids contents, module fineness, bulk density, and mechanical performance that certain aggregate mixtures will present. In the present work, different mixtures of aggregates were made using three types of raw materials: fine sand, coarse sand, and 3/8" aggregate, for which their mineralogical composition was evaluated using X-ray diffraction, the chemical composition using X-ray fluorescence, and its macroscopic structure using optical microscopy. Sixty-six mixture formulations were made, to which variables such as fineness modulus, particle size distribution, void content, and density were evaluated. These data were represented in ternary diagrams. From the gradation studies carried out, six formulations were selected based on the type of aggregate used and the content of voids. With this selection, concrete specimens were made, which were subjected to compression tests, finding that the mixture A 22, with 17 % of voids generated a compressive strength of 22 MPa. The results obtained can be used not only in applications such as zero-set concrete, concrete block masonry, or regular concretes, but also in asphalt pavements, ceramic materials obtained by sintering, and particle-reinforced composite materials.

**Keywords:** particulate reinforced composites; aggregates; size distribution; gradation; particle packing; Portland cement.

### Resumen

La distribución de tamaño, las interrelaciones de gradación y el tipo de agregados, son factores de gran relevancia para el diseño de mezclas en concretos y en materiales de construcción en general, debido a que estos nos permiten obtener información sobre el porcentaje de vacíos, módulo de finura, densidad aparente y el rendimiento mecánico que presentarán determinadas mezclas de agregados. En el presente trabajo se realizaron diferentes mezclas de agregados utilizando tres tipos de materias primas con diferentes granulometrías: arena fina, arena gruesa y agregado de 3/8", para las cuales se evaluó su composición mineralógica mediante

difracción de rayos X, la composición química empleando fluorescencia de rayos X, y su estructura macroscópica mediante microscopía óptica. Se realizaron 66 mezclas, a las cuales se les evaluaron variables como módulo de finura, distribución de tamaño de partícula, contenido de vacíos y densidad. Estos datos se representaron en diagramas ternarios. De los estudios de gradación realizados, se seleccionaron seis formulaciones en función del tipo de agregado utilizado y el contenido de vacíos. Con esta selección, se realizaron probetas de concreto, las cuales fueron sometidas a pruebas de compresión, encontrando que por ejemplo para la mezcla A 22 que con un porcentaje de vacíos de 17 % generó una resistencia a la compresión de 22 MPa. Los resultados obtenidos se pueden usar no solo en aplicaciones tales como concretos con cero asentamiento, mampostería de bloques de hormigón o en los hormigones regulares, sino además en pavimentos asfálticos, materiales cerámicos obtenidos por sinterizado, y materiales compuestos reforzados con partículas.

**Palabras clave:** compuestos reforzados con partículas; agregados; distribución de tamaño; gradación; embalaje de partículas; Cemento Portland.

## 1. Introduction

Public policies and other government's strategies worldwide for the sustainability that decrease the negative environmental impacts of human activities, by a more efficient energy consumption and materials utilization, face serious challenges because they put in a competition environment, economy, food, and energy (Pimentel *et al.*, 1976; Pimentel; Pimentel, 2007; Meadows; Meadows; Randers, 1992). Circular economy (Ning, 2001; Ghisellini; Cialani; Ulgiati, 2016) put into consideration a new paradigm for offer and demand in which materials design plays from the beginning a significant role in the entire process efficiency: new materials with minimal to zero waste. Diverse strategies from materials technology have been proposed to give solutions to some of the above problems, such as materials substitution, increasing product lifetime, product design with few materials (dematerialization), the reusing of materials and components, and recycling (Wang *et al.*, 2019). However, some of these methods have not been successful for economic, legal, and social reasons (Allwood; Ashby; Gutowski; Worrell, 2013). Therefore, one of the main challenges for science and engineering is the optimization of materials via microstructural characterization and materials selection tailored for specific or multifunctional applications (Jiao, 2014).

Nowadays many solid materials used in engineering are fabricated or composed of particles with very wide heterogeneous characteristics such as multiples particle sizes, shapes, and chemical compositions. As a consequence of that, many of these fabricated materials are very heterogeneous in properties. These types of particulate materials are used in important sectors like food (Bayram, 2005), mining (Kandhal; Khatri; Motter, 1992), and construction and infrastructure (Alexander; Mindess, 2010). Also, particulate materials are used from nano (Wang *et al.*, 2012; Colorado; Hiel; Hahn, 2010; Gu *et al.*, 2013), micro and macro scales (Yan *et al.*, 2009; Quiroga; Fowler, 2003; Colorado; Garcia; Buchely, 2016; De-Larrard; Sedran, 1994; Colorado; Yang, 2014). In particulate based materials systems as those described before, properties are the summary of the individual contribution of each particle and by their packing situation in the mix as well (White; Walton, 1937).

The packing mechanisms for solid particle materials are essential for the understanding and optimization of products and processing in industries such as concrete, powder metallurgy, ceramics, granular fertilizers, pharmaceuticals, composite materials, and welding. This topic has increased the number of publications and research that includes fundamental research (including physical and mathematical approaches), and extensive industrial experimentation (Sobolev; Amirjanov, 2004a; Dewar, 1997). The packing density of a granular mix is a function of the shape and size of the dispersed solid particles (Brouwers, 2006; Smith; Midha, 1997). The physical-chemical properties of materials constituted by granulated particles are determined by a complex combination of factors such as the particle sizes, particle shapes, surface texture, chemical compositions, and particle packing (Herrmann; Mahmoodi; Wackenhut, 2003; Kolonko; Raschdorf; Wäsch, 2010). It is generally

accepted that the packing optimization can produce the strongest materials, with the highest modulus of elasticity, shrinkage, and creep performance (Gil; Khayat; Tutikian 2019). In general, all these advantages are connected with a sustainable process. Thus, packing and gradation optimization are from the biggest interest in both industry and science.

In the search for the ideal packing model for concretes, several methods have been developed, such as Fuller (Gong; Zhang; Wang; Zong; Lu, 2015), Shilston (Shilstone, 1990), and ACI (Oh; Lee; Kim; Lee, 1999). Although they are mostly based on the maximum packing density or minimum void contents, the comparison is difficult to establish among them because they start with different parameters and for some of them, few and not comparable data is available. Therefore, the fact that there is a good number of models reveals that there is a complex problem still far from being solved. The perfect packing model has been a subject with a long history (Weaire; Aste, 2008), studied for even more general systems than when concrete is considered with all their complex materials mix with cement, water, aggregates, and pozzolanic components. When just the aggregates or particles are considered, the studied problem can be implemented either in ceramics, concrete, or other granular materials (Herrmann; Mahmoodi; Wackenhut, 2003). Polydisperse granular and other models are known to give maximum packing densities fundamentally studied in very simple particles shapes (Herrmann; Mahmoodi; Wackenhut, 2003; Kolonko; Raschdorf; Wäsch, 2010; Brouwers, 2006; Sobolev; Amirjanov, 2004b), with theoretical models (Herrmann; Mahmoodi; Wackenhut, 2003; Kolonko; Raschdorf; Wäsch, 2010; Brouwers, 2006; Sobolev; Amirjanov, 2004b), when large and small particles are added not carefully in the mix, and then being a potential source of problems such as voids and segregation. In a real mix, controlling the exact particle size distribution is not possible, when we consider large scale engineering applications with billions of different particles. Further models for irregular particle shapes have been proposed as well (Smith; Midha, 1997).

Today, multiple concrete applications in the construction and infrastructure industry require the development of methods and procedures to predict and optimize their properties and part performance from the raw materials and components. The empirical and experimental optimization of compositions (mix design) is a complex challenge due to the wide particle size distribution in the mix, from values of 1  $\mu\text{m}$  (such as cement and additives) to 10 mm (such as sand, fillers, and aggregates) (De-Larrard; Sedran, 2002; Hüsken; Brouwers, 2008). Mix design aims to produce a material that meets the required performance for a given application, such as the number of mineral aggregates that optimize the density for a given compressive strength. A high aggregate packing density can promote a high compressive strength (Jones; Zheng; Newlands, 2002) and a decrease in the cement consumption, which clearly decreases the final product and is more environmentally friendly as well. In many companies, such as in a concrete block masonry plant, the most common procedure for a mix is to produce some trial mixtures with different cement contents, using the typical low technology apparatus available in a block plant, which can be tested for compression strength. In the last century, several models for mix design have been used extensively in diverse materials and systems (Shen; Yu, 2011; De-Larrard, 1999; Su; Hsu; Chai, 2001; Sobolev, 2004).

In this paper, a very simple experimental method using three types of aggregates as raw materials were used (sand, coarse sand, and 3/8" aggregates) to study the effect of aggregate type and gradation interrelations in properties as voids contents and fineness modulus is presented. Fineness modulus, particle size distribution, relative and apparent densities, void contents, and optical microscope images were obtained for all the aggregate combinations investigated.

## **2. Description of the problem**

As described earlier in the introduction, the packing of a particulate material allows knowing other physical characteristics in the construction or composite materials, which enable the characterization and optimization of a process. In the case of construction materials such as concrete, the mixture of different size distributions

of aggregates present different packings, which when quantified makes it possible to have a notion of bulk density, percentage of voids or mechanical performance that goes to present the already formed material, for which, the packaging research, form, and other characteristics of the solid materials represent a tool of great importance for the industry. Thus, it can mean infinite advantages concerning the transport, manufacture, and performance of a material, which is directly related to the profitability and efficiency of the process.

### 3. Methodology

All materials used in this research were mineral aggregates supplied by Conasfaltos S.A. from Colombia: fine sand, coarse sand, and 3/8" aggregates, which were analyzed and used following the experimental design summarized in Table 1. In these experiments, the factors are the aggregates contents and aggregate types; while the response variables are void contents, fineness modulus, apparent density, compressive strength, and compressive strength. These raw aggregates were characterized by gradation experiments (sieve analysis). Aggregates are from Alluvial deposit, with 56.3 % of potentially alkali reactive aggregates: 9.4 % of quartzite fragments and 4.6 % to highly reactive chert fragments. 42.3 % correspond to fragments of silicified amphibolites and andesites, which are considered moderately to weakly reactive with alkali-silica. The content of non-reactive constituents is an average of 43.7 %.

Aggregates were combined with mechanical mixing. Subsequently, fineness modulus was determined by using the standard ASTM C136/C136M - 05. Figure 1a shows a representation in a ternary phase diagram of all samples studied in this research, corresponding to materials combinations confirmed just by the raw aggregates mentioned above (Table 1), placed in the ternary diagram on the corners. The mix of two aggregate types in the diagram is located in the exterior lines (axis) of the diagram, and the mix of three components is found inside the diagram, inside the triangle. For all experiments, aggregates were dried in a furnace at 100 °C for 1 day to remove all the unbounded water.

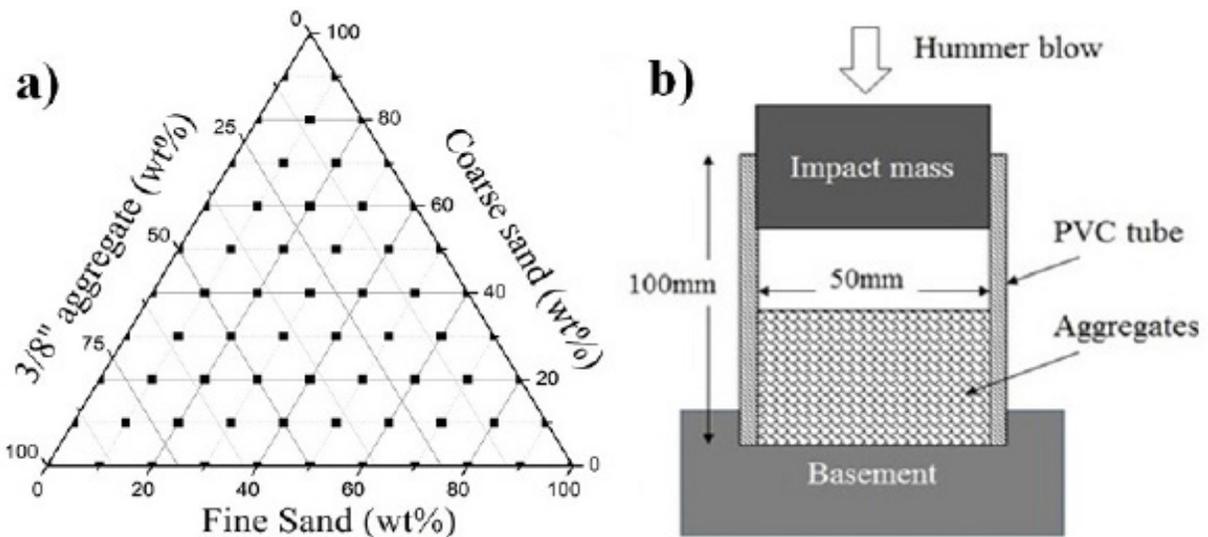


Figure 1. a) Ternary diagram showing all sampling from pure to combinations of the different aggregates used this research, b) schematic representation of the compaction experiment conducted  
Source: own.

Samples were compacted in a tamping rod device represented in Figure 1b, which shows a schematic image of the compaction experiment conducted over the aggregates. Following the procedure from the ASTM C29/C29M-17, with the container first at 1/3, then at 2/3, and finally full of aggregates, samples were submitted to a total of 25 hummer impacts as represented in Figure 1b. By comparing the weight before and after the

compaction procedure as described before, the aggregate’s weight and its volume were determined, and thus, its voids contents and apparent density were established for each sample. Relative density tests were estimated under the ASTM C128-15 and ASTM C127-15 standards. Apparent density and voids contents in the aggregates were tested as well in all samples, following the ASTM C29/C29M–17 standard. In addition to gradation tests, particle size distribution was investigated using optical microscopy images processed with the Image-J software for image digital analysis. 50 images were taken for each aggregate size. Particle size was the average of two different measurements over each particle. Several of these results were finally plotted in ternary diagrams or combined to establish interrelations among them.

**Table 1.**  
*Experimental design for a combination of the different aggregates*

Sample Name	Aggregates			Sample Name	Aggregates		
	Fine sand	Coarse Sand	3/8"		Fine sand	Coarse sand	3/8"
A1	80	10	10	A34	10	30	60
A2	70	20	10	A35	10	50	40
A3	70	10	20	A36	10	40	50
A4	60	30	10	A37	10	0	90
A5	60	10	30	A38	20	0	80
A6	60	20	20	A39	30	0	70
A7	50	10	40	A40	40	0	60
A8	50	40	10	A41	50	0	50
A9	50	30	20	A42	60	0	40
A10	50	20	30	A43	70	0	30
A11	40	50	10	A44	80	0	20
A12	40	10	50	A45	90	0	10
A13	40	40	20	A46	10	90	0
A14	40	20	40	A47	20	80	0
A15	40	30	30	A48	30	70	0
A16	30	60	10	A49	40	60	0
A17	30	10	60	A50	50	50	0
A18	30	50	20	A51	60	40	0
A19	30	20	50	A52	70	30	0
A20	30	40	30	A53	80	20	0
A21	30	30	40	A54	90	10	0
A22	20	70	10	A55	0	10	90
A23	20	10	70	A56	0	20	80
A24	20	60	20	A57	0	30	70
A25	20	20	60	A58	0	40	60
A26	20	50	30	A59	0	50	50
A27	20	30	50	A60	0	60	40
A28	20	40	40	A61	0	70	30
A29	10	80	10	A62	0	80	20
A30	10	10	80	A63	0	90	10
A31	10	70	20	A64	0	0	100
A32	10	20	70	A65	0	100	0
A33	10	60	30	A66	100	0	0

Source: own.

XRD characterization for the aggregates was conducted in an X’Pert PRO diffractometer with Cu K $\alpha$  radiation of 1.5406 Å). Random samples were selected and mixed with residual powder from the aggregate batch and then all mixed and ground manually in a mortar until the ultra-fine powder was obtained. The scanning was performed with between 10 and 80°, with a step size of 0.02°. X-ray fluorescence (XRF) for oxides identification was conducted in an ARL 8680 apparatus following the ASTM C114-03 Test. Powders were dried at 105 °C before the test. Loss of ignition was determined at 1000 °C by thermogravimetric analysis (TGA) in a Perkin Elmer Instruments Pyris Diamond TG/DTA equipment, with a temperature ramp of 10 °C/min, and a nitrogen flux of 0.06 L/min.

White Ordinary Portland Cement (WOPC) from a local manufacturer from Colombia (with max. 6.0 wt % MgO, and max. 3.5 wt % SO<sub>3</sub>) was used in combination aggregates. Samples based on the of aggregate combinations A14, A22, A34, Ag4, A65, and A66, were selected among all other samples not only to be tested in compression tests but also to have samples with low, medium, and high values of voids contents samples and see the effect as cement paste matrix fill all this space in mechanical properties. As a binder, Ordinary Portland cement was used for the manufacturing of the samples, see Table 2, with a ratio W/C = 0.4 and with 40 wt % of a combination of aggregates (A14, A22, A34, A64, A66, and A65 from Table 1). The cylindrical samples were cured for 28 days in a container closed to air contact. Thereafter, samples were airdried by three days and tested for compression tests. Compression tests were conducted in a Shimadzu universal testing machine. A set of 5 samples was tested for each of the combinations, at a crosshead speed of 1 mm/min.

**Table 2.**  
*Composition of concrete samples for compression testing*

Sample mixtures of aggregates (see Table 1)	Mixtures of aggregates (wt %)	Portland cement (wt %)	Ratio W/C
A14	40	60	0.4
A22	40	60	0.4
A34	40	60	0.4
A64	40	60	0.4
A65	40	60	0.4
A66	40	60	0.4

Source: own.

## 4. Results and discussion

Aggregates were observed by optical microscopy as presented in Figure 2. These aggregates were obtained from a quarry located in Bello, Colombia. These aggregates show both irregular and sharp edges.

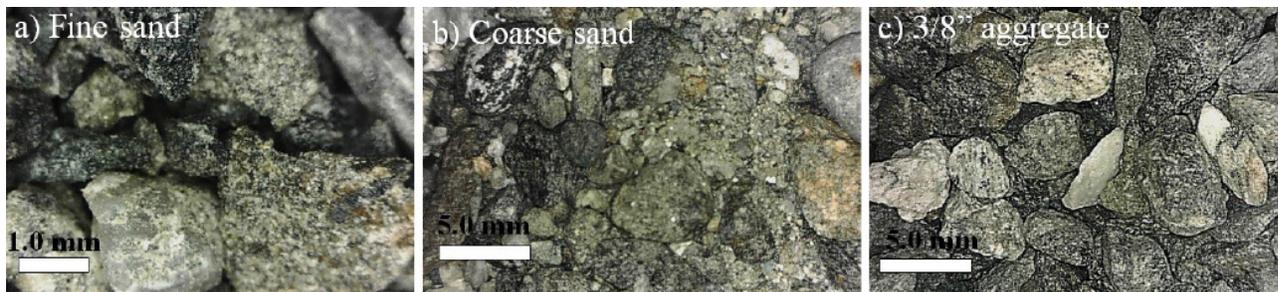


Figure 2. Optical microscopy images from aggregates used in this research

Source: own.

The XRF results summarized in Table 3 show that most of the materials are in the form of silicon and aluminum oxides. Calcium and iron oxides were also significant amounts. The loss of ignition (LOI) of 3.7 wt % shows the volatile materials are quite low. On the other hand, Figure 3. summarizes XRD results, the technique only able to reveal the crystalline phases from the aggregates sample. Therefore, quartz ( $\text{SiO}_2$ ), Calcite ( $\text{CaCO}_3$ ), hematite ( $\text{Fe}_2\text{O}_3$ ), and alumina ( $\text{Al}_2\text{O}_3$ ), were found in 71, 23, 5.5 and 0.5 wt % respectively.

**Table 3.**

X-ray diffraction results over the steel dust, with loss of ignition of 3.7 %

Compound	SiO2	Al2O3	CaO	Fe2O3	MgO	Na2O	TiO2	LOI
Wt %	53.2	18.0	9.6	8.4	3.9	1.9	0.7	3.7

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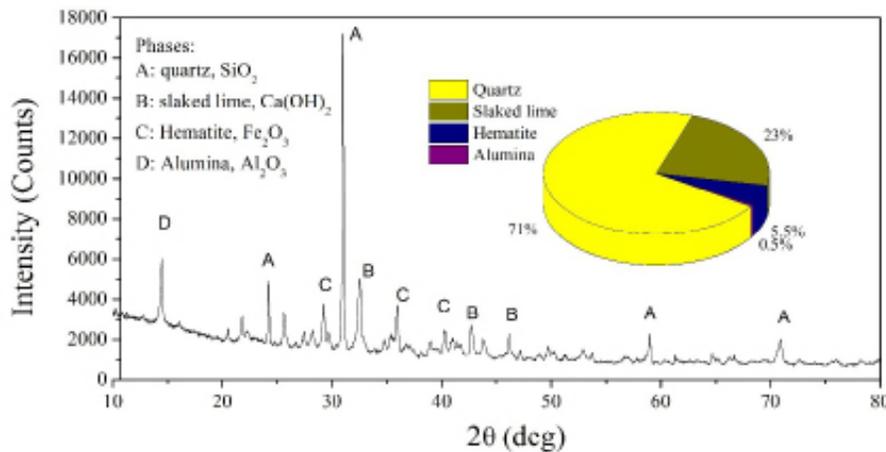


Figure 3. X-ray diffraction from the aggregates used in this research

Source: own.

From multiple optical microscopy images at different magnifications, like those shown in Figure 2, particle size distribution curves were obtained, see Figure 4 a, b and c are particle size distributions for fine, coarse, and 3/8" aggregates. Fine and 3/8" aggregates curves have a closer approach to ideal normal distributions when compared with coarse aggregates. The mean and standard deviation results are summarized in Figure 4d. The curve has a perfect parabolic trend and the equation is displayed in the image. The increase in the standard deviation for coarse aggregate could be associated with distribution type.

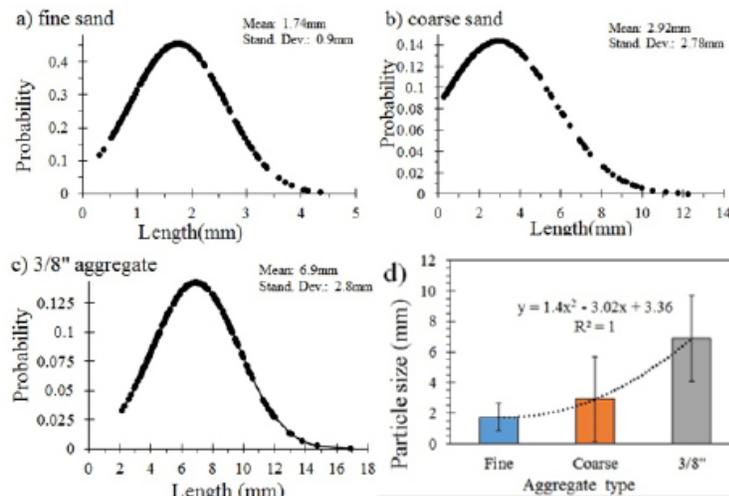


Figure 4. The particle size distributions for fine, coarse, and 3/8" aggregates are presented in Figura 4 (a), (b), (c), and (d) summary of results

Source: own.

Figure 5 shows the results for sieve dosing experiments corresponding to each of the raw aggregate investigated. Figure 5a for fine sand aggregate shows a sieve distribution towards the left side, which are the smallest sizes, with all the particles between 0 and 5 mm and a retained peak at 1.9 mm sieve size. Figure 5b for coarse sand aggregate is also charged toward the left side, although two peaks seem to appear near 1 and 4 mm of retained contents.

This is due to several particle size distributions having significant influence in the mix. Figure 5c corresponds to the sieve dosing for 3/8" aggregates, which shows the most symmetric curve of the three groups of aggregates, with a peak at 5.5 mm sieve size. Figure 5d summarizes the main sieve peak positions and their corresponding retained value. As expected, as the particle size increases from fine sand to 3/8" aggregate, the sieve peak position increases as well. In the case of the retained contents, both sand and coarse sands have similar values for the peak, although the coarse sand has a clear secondary peak not included here, differently from the 3/8" aggregate that triple these values.

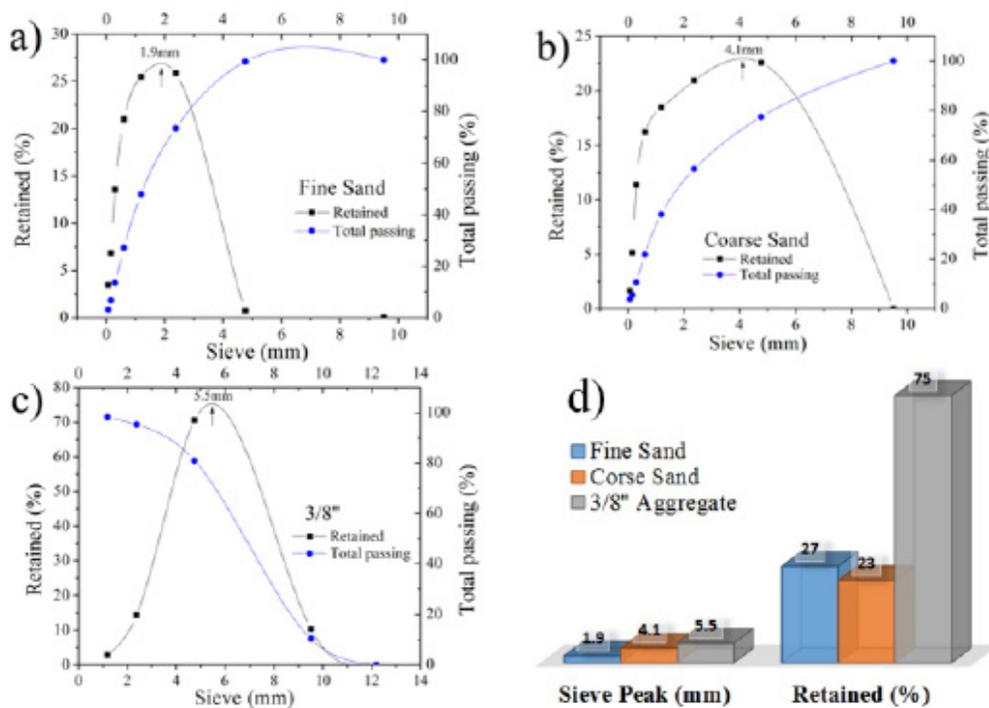


Figure 5. Sieve dosing experiments for aggregates used in this research  
Source: own.

In the concrete manufacturing, it is typical to find up to two, three or more types of aggregates used to decrease the amount of cement used in the mixture, controlling the volumetric changes and increasing mechanical strength to the material. Thus, the results obtained for the percentage of voids for all the mixtures were analyzed in two parts. First, the behavior was observed for the mixtures with two types of aggregates (Figure 6). Second, a global analysis was performed (Figure 7) concerning the contents of the void, which appear in mixtures of 1,2 and 3 types of aggregates.

Figure 6 summarizes results for voids contents for a mix of three aggregate types: a) mixing of fine sand and 3/8" aggregates, b) mixing of fine sand and coarse sand aggregates, and c) mixing of coarse sand and 3/8" aggregates. All curves were fitted with polynomial equations, which showed that the combinations among fine sand and 3/8" aggregates and coarse sand and 3/8" aggregates correlate 1.0.

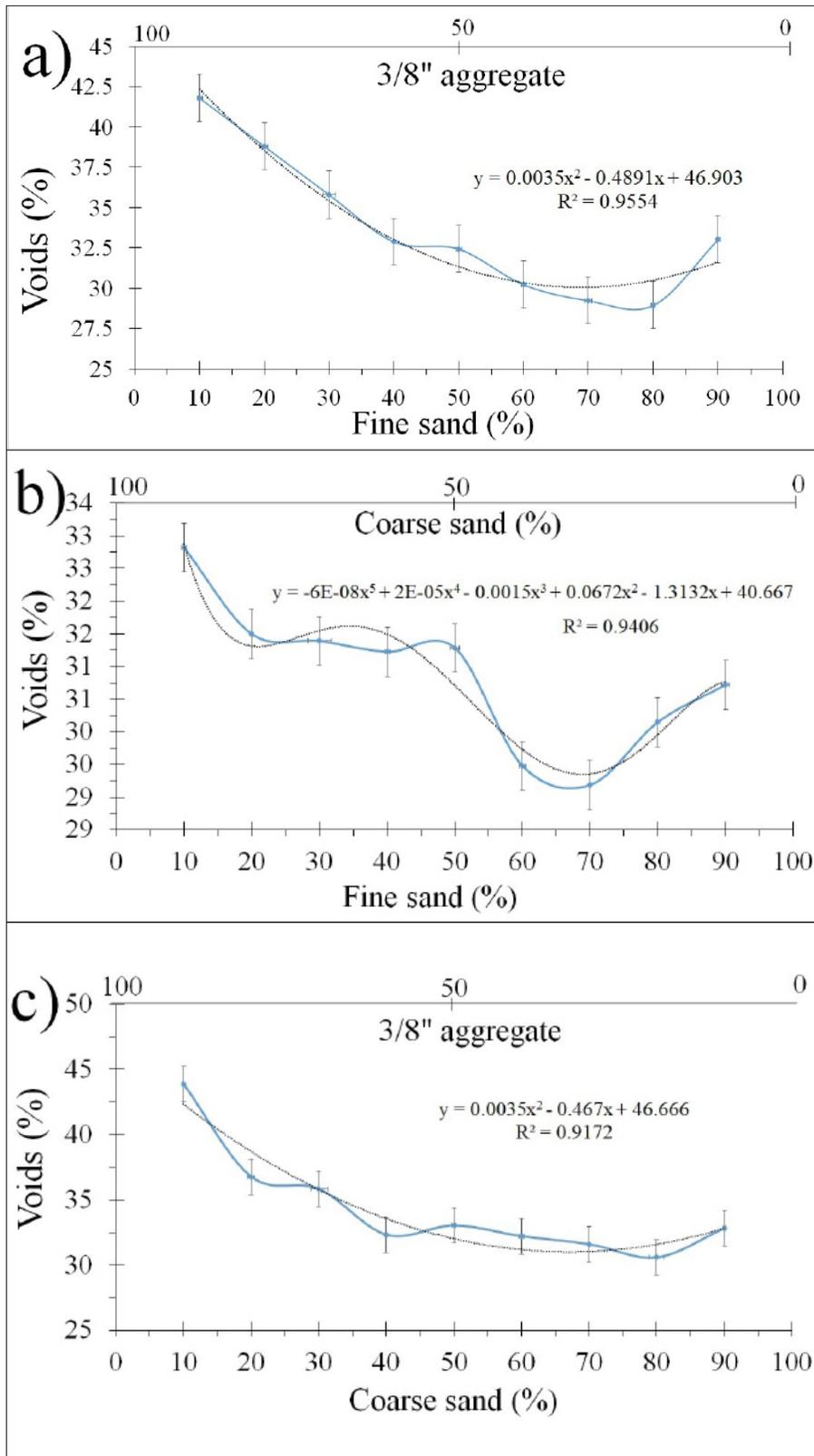


Figure 6. Voids contents for **a)** mixing of fine and 3/8" aggregates, **b)** mixing of fine and coarse aggregates, **c)** mixing of coarse and 3/8" aggregates

Source: own.

With all the experiments conducted, several ternary diagrams were constructed. Figure 7 is a ternary diagram for void contents of the three types of aggregates, with the highest void contents when the combinations go towards the mix of fine sand and 3/8" aggregates. The lowest voids contents appeared in several separate spot areas, which evidence the complex interrelations among different particle size distributions interacting in a multivariable material or system.

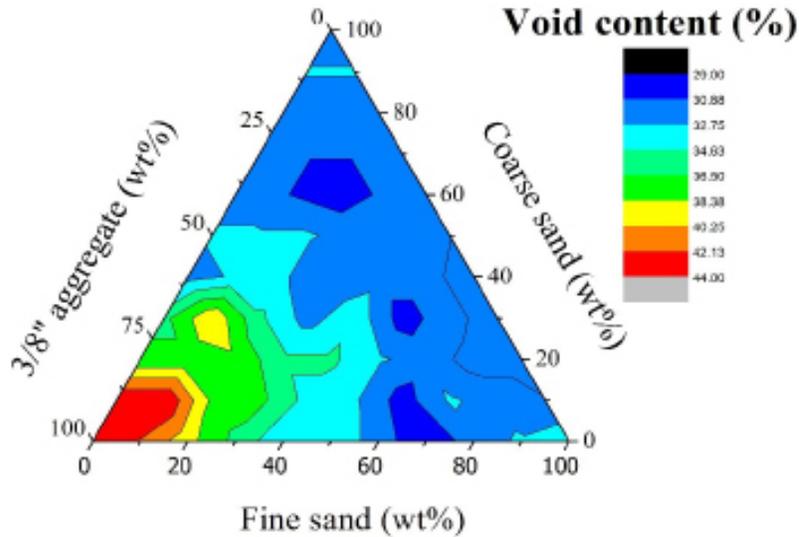


Figure 7. Ternary diagram for void contents of the three types of aggregates  
Source: own.

On the other hand, the fineness modulus from Figure 8 showed a clear trend from right to left of the diagram, corresponding to the combination of coarse-fine sand aggregates, and the combination fine sand-3/8" aggregates, respectively. Therefore, the combination of coarse sand-3/8" aggregates have a less significant impact on the fineness modulus than the other combinations.

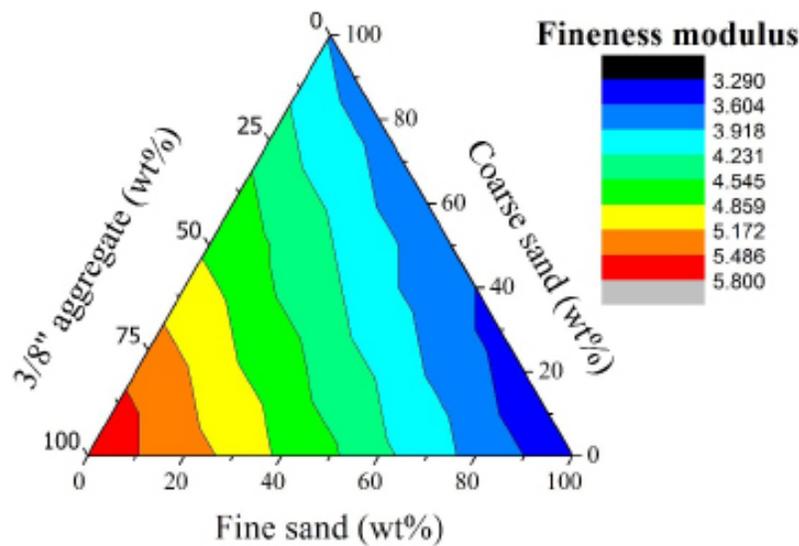


Figure 8. Ternary diagram for fineness modulus of the three types of aggregates  
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Finally, Figure 9 is a ternary diagram for bulk density. There are separated spots for high densities and a sole spot for the lowest density on the fine sand-3/8" aggregates combination.

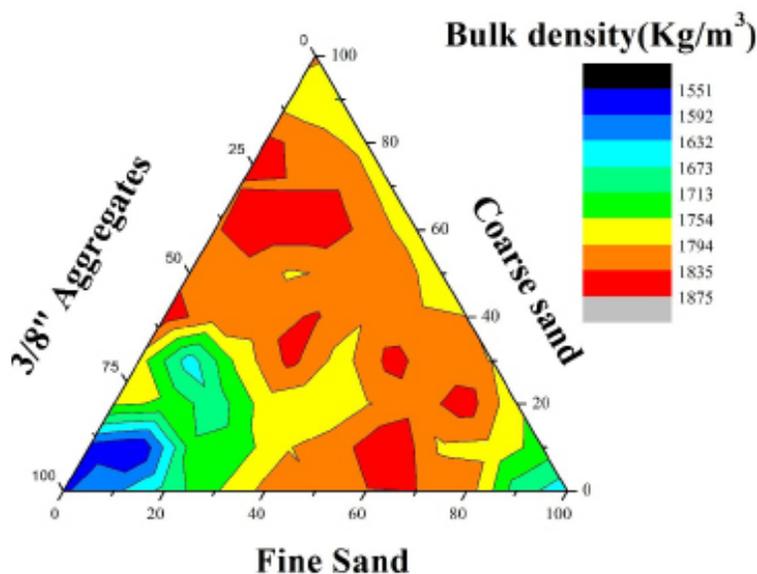


Figure 9. Ternary diagram for bulk density of the three types of aggregates  
Source: own.

Figure 10 shows compression test results for six selected formulations of the aggregate combinations, nominated to have diverse spectra of results. The graph shows the cement paste content in volume, which approximately corresponds to the contents of the void of the aggregate mixed studied before without any filling cement paste. Samples' results in this image appeared in terms of the cement paste contents, from the highest to the lowest value. There is not a clear trend until we analyze in detail the results regarding the aggregate type. If we just consider the samples with only one aggregate type (A64 for fine sand, A65 for coarse sand, and A66 for 3/8"), as shown in Figure 10 b, it is clear that there is an aggregate type that maximized the compressive strength.

In this case corresponded to samples A65, with a particle size mean value of 2.9 mm given by the tests summarized in Figure 4 b. In this case, samples with higher compressive strength showed the minimum amount of cement paste by volume, which can be explained as a consequence of the particle distribution itself, which more likely allows particle to particle interact in the concrete and therefore when the material is subject to compression tests, these particles are quite well connected and thus then the main contribution to the composite is by their particle to particle compression. This can be also inferred from the distribution itself. When we compare the same graph (see Figure 4 a, b, and c), the corresponding distribution to sample A65 is less symmetrical and more concentrated in the largest values, which is associated with less variable particle sizes. For the other two samples (A64 and A66), both the shape of the particle size distribution (see Figures 4a and c) and compressive strength values were very similar.

Thus, from Figure 10 a, from the three samples that use a combination of the three aggregates used in this research (A14, A33, and A34), it is observed that samples A22 has the larger amount of aggregate coarse sand, which is related to results previously described for sample A65. From the other two samples, A34 had better compressive strength than A14 which can be related to bigger particle size for sample A14, show the complexity of these samples and the multi-parameter involved just by combining a particle size distribution with cement paste, in the case of these three samples which contain a combination of aggregates (A14, A33, and A34), the sample with the highest compressive strength was the one with the highest cement paste used, which is not correlated with the trend revealed in Figure 10 b.

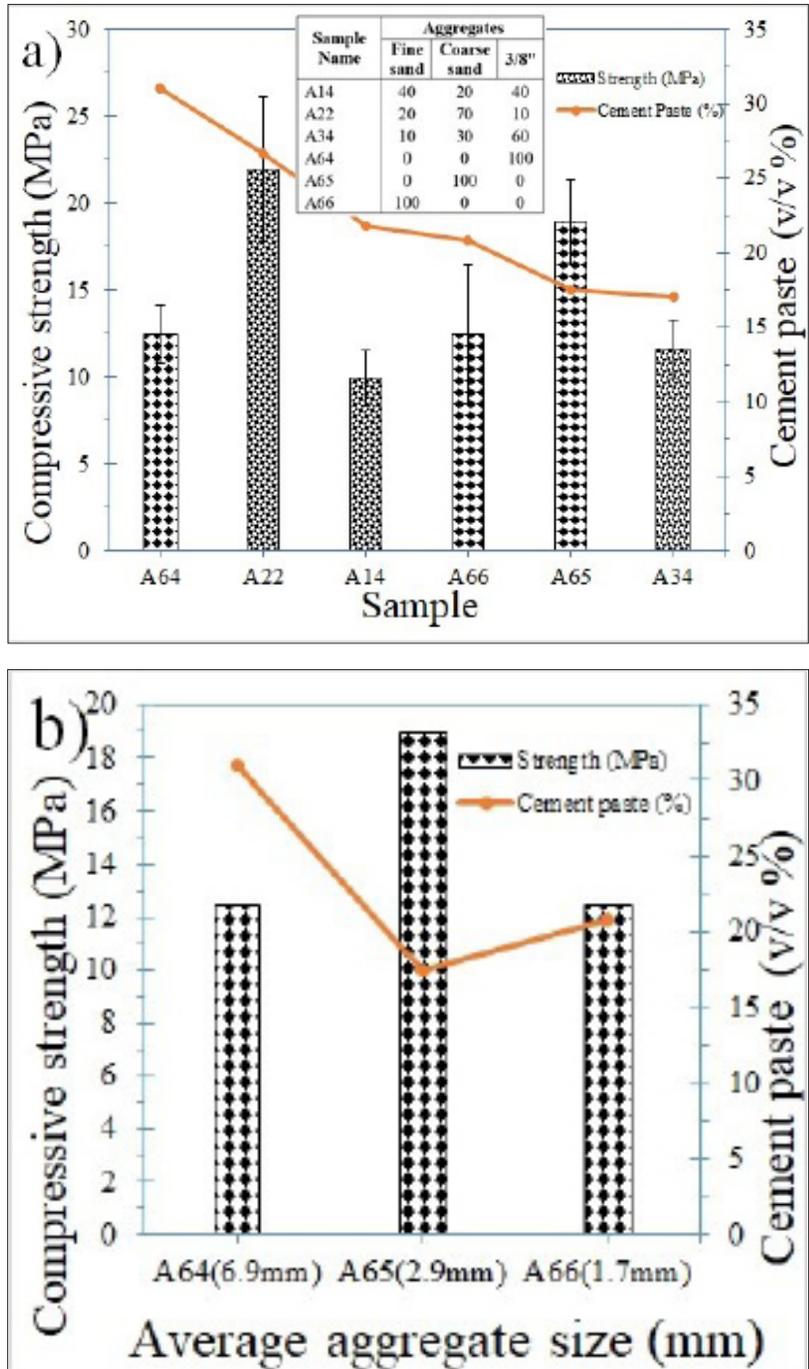


Figure 10. Compressive strength for some selected compositions  
Source: own.

## 5. Discussion

The procedure showed in this research is very simple, inexpensive, and effective for studying any type of solid particle system where the mix design, gradation, or particle size distribution is important for determining other derived properties. This process can be easily conducted in companies that process these materials worldwide, which knowledge can lead in a very well know effect on reducing cement and other binding materials, therefore decreasing production costs (Lindquist *et al.*, 2015), water demand (Damtoft *et al.*, 2008), and CO<sub>2</sub> released to air

(Worrell *et al.*, 2001). Also, the optimization of gradation to an ever best-compacted mix of aggregates, open up more even ultra-high and ultra-strong performance materials and buildings (De-Larrard; Sedran, 1994). One of the possibilities is the way the aggregate industry works with supplying aggregates to other companies or for their projects, as a new business model can appear if they supply specific gradation formulations for each client, which certainly can be achieved with the proposed and simple method of this research.

The chemical analysis conducted by XRF and XRD is very complementary. While the quartz ( $\text{SiO}_2$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ) contents are very acceptable in terms of the contents and say these two phases are very crystalline as confirmed by XRD, the results showing lime ( $\text{CaO}$ ), calcite ( $\text{CaCO}_3$ ), and alumina ( $\text{Al}_2\text{O}_3$ ) seem to be a different case. When compared the alumina contents obtained with XRF is low concerning XRD. This is associated with alumina participating mainly as part of amorphous compounds, such as the typical calcium-aluminates and alumino-silicates, typically found in Colombia. In the case of calcite, carbon is difficult to detect by XRF, and thus XRD here was very important to determine the presence of this very common compound in aggregates (West, 2001).

In the case of the contents of the void, the ternary diagram plots show areas where the manufacturer can easily incorporate a specific particle distribution that either fills the mix to reduce voids and optimize compressive or density, or either prepare a mix to generate a particular void size contents such in the case of porous Portland cement (Chindaprasirt *et al.*, 2008) or asphalt concretes (Goh; You, 2011), or in the case of concrete block with high compressive strength (Sukontasukkul; Chaikaew, 2006). In case of filling voids, there is a great opportunity in adding multiple available ceramic wastes that have very specific particle distributions (Loaiza; Cifuentes; Colorado, 2017; Colorado; Colorado, 2016; Haibin; Zhenling, 2010; Colorado; Yuan; Guo; Juanri; Yang 2014). Moreover, the current investigation is part of a national strategy not only for the company involved but also for the government in implementing strategies such as the need of a new model in the circular economy in Colombia (Colorado; Echeverry; Colorado, 2019; Ordóñez; Echeverry; Colorado, 2019) and company-universities sustainable projects (Agudelo; Cifuentes; Colorado, 2019).

Concerning the gradation and particle size distribution tests, they show to be very complementary, and in fact, the summary results from Figure 4d and Figure 5d show an increasing trend when particle and sieve sizes increases as the aggregate size increases. Moreover, in the case of sieve results for coarse fine aggregate two peaks appeared contributing to the curve, which has been associated with two significant particle sizes competing in the mix. This behavior was not observed for the fine sand and 3/8" aggregate types, this is for the smaller and greater particle size for the coarse sand aggregate, which suggests this coarse sand has some elements characteristics of the other two aggregates gradations. This observation is also shown in the voids contents curves from Figure 6, where the combination curves revealed that coarse sand has a stronger effect in changing the ideal smooth combination curve, as it is observed when it compared the fine sand and 3/8" aggregates having the smother curve when no coarse sand was involved.

Figure 7 show some spots that minimized voids' contents. For a combination of 3/8"-fine sand- coarse sand, the respective combinations these materials in wt % such as 20-20-60, 20-50-30, and 20-70-10, can be obtained from the diagram. Thus, a combination with 20 wt % of 3/8" aggregates is a beginning for obtaining a gradation with minimal voids, for the materials used in this research. For fine and coarse sand combinations, we can conclude that a difference between 1.7 and 7 times between these two aggregates is also good for a mix of aggregates with low void content. On the other hand, also from Figure 7, in general, a mix with the highest void contents can be obtained when 3/8" aggregates are more than 90 wt %, fine sand less than 10 wt %, and coarse sand is less than 15 wt %.

Regarding the compressive strength values summarized in Figure 10, some general results can be very useful for the materials used. The first one is the fact that using the coarse sand with cement paste produced the best results, in both cases, just for cement paste-coarse sand samples, and for cement paste with a combination

of fine sand, coarse sand, and 3/8" aggregate types. The second important result is that depending on the aggregate type and the shape or type of the particle distribution, very diverse concrete materials can be tailored for different applications. Finally, it is also important to mention that many parameters and variables are involved in this problem, which is evidenced by the very diverse particles sizes and shapes used (even when using just one type of aggregate type), which make results not only hard to generalize in cases the aggregate is changed, but also difficult to extrapolate to different manufacturing conditions. Therefore, it is clear that this study is recommended to be conducted for each aggregate source, as not only the chemistry (such as reactivity, pH) but also the morphology varies a lot even for the same sample.

The present study highly motivated by collaborative results with a local Company, who is leading innovative but simple procedures to find not only value to its aggregates and other particulate building materials, but also, able to be implemented in its Research and Development department. Thus, different matrix materials such as phosphates (Colorado; Yang, 2014; Colorado *et al.*, 2011), geopolymers (Colorado; Hahn; Hiel, 2011), high-performance resins (Colorado *et al.*, 2014; Bell; Driemeyer; Kriven, 2009), and complex aggregate-solid waste composites (Bekir; Bilir, 2009), can be optimized upon the correct use of their particle reinforcements. Further developments for smaller particle such in nanocomposites (Guo *et al.*, 2008; Guo *et al.*, 2006; Hussan; Hojjayi; Okamoto; Gorga, 2006) will require more research as the interfacial forces are very large but an investigation is very open particularly for the particle reinforcement point of view.

## 6. Conclusions

The aggregate type and gradation interrelations using sieve tests and particle size distributions as were studied in this research allowed to specifically know the region where void contents are maximum and minimum by different ways, first by combining materials by two, then, by combining materials by three in a ternary phase diagram. Also, fineness modulus and density were investigated. The combination aggregates that maximizes voids' contents can be obtained for 3/8" aggregates more than 90 wt%, fine sand less than 10 wt %, and coarse sand is less than 15 wt %. For minimal void contents, several combinations worked well as explained before, which reveals the complex nature of particle and gradation interrelations in determining properties of a mix. Compression tests showed a very complex structure-property relation when the aggregate formulation is changed in concrete, and therefore it is very important to conduct similar studies any time the application requires it. Even in the case of waste and nature fiber particulate based composites can be optimized via particle size distribution as was shown in this research.

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