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Use of Furnace Steel Slag for Road Construction With Rigid Pavements

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Abstract: The rigid pavement needs constant maintenance for its good preservation in an efficient, fast and economical way, meeting the needs and requirements to ensure that the rigid pavement constructions can be developed with the corresponding nature for a work, for this it is necessary to evaluate the real state of the pavements, generate a vademecum of avenues that integrate the pathologies in the concrete, in this way it will be possible to formulate the best solutions. A guideline that allows to reflect on the urgency of following a study in the construction of conventional rigid pavements, is the one located on the Oruro-Toledo highway in Bolivia, listing problems such as: (frost, increase of traffic, lack of maintenance), damaging its structure. The objective of this research is to design the proposal to use a furnace steel slag that allows the placement of a high strength concrete for a rigid pavement with which Bolivia would access the stage of reducing, reusing and recycling steel material for the design of new concrete in roads, in addition to reducing the exploitation of natural aggregates, knowing that the slag absorbs less water being a positive property to generate greater resistance. The proposal to use this new dosage is exclusively directed to the international route Oruro-Pisiga, section Oruro-Toledo, because the slag would supply for a future replacement of slab to this section in an experimental way, as in the beginning of the largest urban road project in the United States, encouraging Bolivia to improve its roads in Latin America. The outcome of this research shows that the concrete reached a compressive strength greater than 400 Kg/cm^2 with 50% slag as aggregate, the design also encourages the industrialization of a Portland cement type II in Bolivia.

Key words: pavement, slag, strength, recycle

1. Introduction

Bolivia is a relatively young country with relatively little experience in the construction of rigid pavements. In 2001 a rigid pavement road project of approximately 38 kilometers in length was completed, the Oruro - Toledo section, a fundamental road network linking the Plurinational State of Bolivia with the Republic of Chile.

The failures of this first section are due to administrative problems that took 4 years in its location, passing through several companies, which caused the decrease of hydrological studies and soil mechanics, due to this complication the pouring of the rigid pavement derived in failures already in its first days, fissures and cracks superficially sealed with tar that nowadays increased, the road surface has a spider web effect that is uncomfortable and dangerous for the comfort of the user.

The research proposes a replacement of rigid pavement with high performance using furnace steel slag, an innovative proposal for road engineering in Bolivia, being a technological and environmental adaptation due to world energy changes, as engineers we must raise awareness to recycle metallurgical waste, encapsulate them in pavements, reducing toxic waste to the environment and decreasing global warming.

As a developing country in road and bridge engineering, the research aims to contribute to technological development with the use of a recycled

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material, including it in the list of countries where the use of recycled slag for road construction is standardized, increasing the useful life of the project by being a high strength concrete and reconditioning the Oruro Toledo section, in addition to proposing a type II portland cement.

1.1 Location

From the Andes mountain range of Bolivia starting in the south of the department of Oruro at 3735 m.a.s.l. (meters above sea level), culminating after 38 km in the town of Toledo at 3715 m.a.s.l., with an annual rainfall of 382 mm (millimeters), and a maximum temperature of 22°C in summer, dropping to -15°C in winter, Fig. 1 shows the area.

Fig. 1 Satellite image of the location of the 38 km section Oruro-Toledo.

2. Description of the Problem

It was concisely mentioned in the introduction the problem of the section being the first road built with rigid pavement that suffered contract declines, there was a range of losses of studies and designs, because of the budget invested it was not economically viable to redo them by building the section with the technical data that was available, that is where the famous phrase of Matthew W. Witczak [1] bursts in. Witczak [1] emphasizing that pavement engineering "is the art of using materials we do not fully understand, in ways we cannot accurately analyze, to support loads we cannot predict, so that no one suspects our ignorance".

A simplistic phrase but dismembering it in the investigated road is compatible with its current problems, as a practicing engineer it is arbitrary and negligent to propose a solution to the problem without having identified the main causes and current state of the road, then, the problems of the section are presented to support and propose the replacement of its wearing course.

2.1 Serviceability Study

Information was collected from the ABC (Administradora Boliviana de Carreteras) where technical information was obtained on the section, the international roughness index (IRI) and serviceability (PSI), the section was visited to verify the validity of the data collected, showing that the section is in poor condition and an in-situ roadway auscultation was performed.

Fig. 2 shows the current state of the road; the cracks have been gradually increasing for more than 20 years, as well as the current ESALS (Equivalent Standard Axle Load) of 6109, since it is a very busy international road; as can be seen, it has a spider web effect that increases the risk factor for the user and reduces the comfort of vehicular handling to the design percentile of the road.

Fig. 2 Identification of fissures and cracks in the roughness auscultation of the Oruro-Toledo section.

These structural failures were caused by the poor foundation of the structural layers using soft material and lack of water drainage, in addition to oversizing the slabs with measures of 4 m. by 4.50 m. and a thickness of 0.24 m., causing that after a few days of the construction, the roadway was damaged. In many sections the slabs were replaced immediately, but over the years the problem increased along the entire section, which led to annual roughness studies to detect new cracks and seal them.

As shown in Fig. 3, to determine values in the functional condition of a road in an effective way, the technical study carried out with the IRI is taken into account, which generates the serviceability of the road, according to the "American Association of State Highway and Transportation Officials" AASHTO, the performance of a pavement should be quantified in terms of its serviceability, the final results of the IRI are the PSI (serviceability index) that in the present investigation 86% of the road is in poor condition so its replacement is recommended.

2.2 Pathology Study

Time shows that the mixture of aggregates, cement, water and admixtures, depending on their compositions, proportions and in contact with external agents interact in such a way as to cause the appearance of failures in the concrete that can alarmingly reduce the useful life of a rigid pavement, the accumulated errors in the construction phase and the maintenance phase continue to be the predominant cause for the study of pathologies in the material. Reinforced concrete is resistant to tension and compression, but it is not immune to its environmental, meteorological and working conditions.

Fig. 4 shows the extraction of cores to determine the deterioration of the concrete in its anatomy and perform compression studies, in addition to identifying a map of internal cracks that will be useful to have a basic knowledge of the trajectory of water in the rainy season, causing corrosion of reinforcements and by punctual efforts of the tires the massive cracking on the surface, in the same way agents of the washing of fine material between the base layer and the concrete, a phenomenon that leads to wear of the concrete at the edges when there are impacts between slabs due to the weight caused by vehicular traffic.

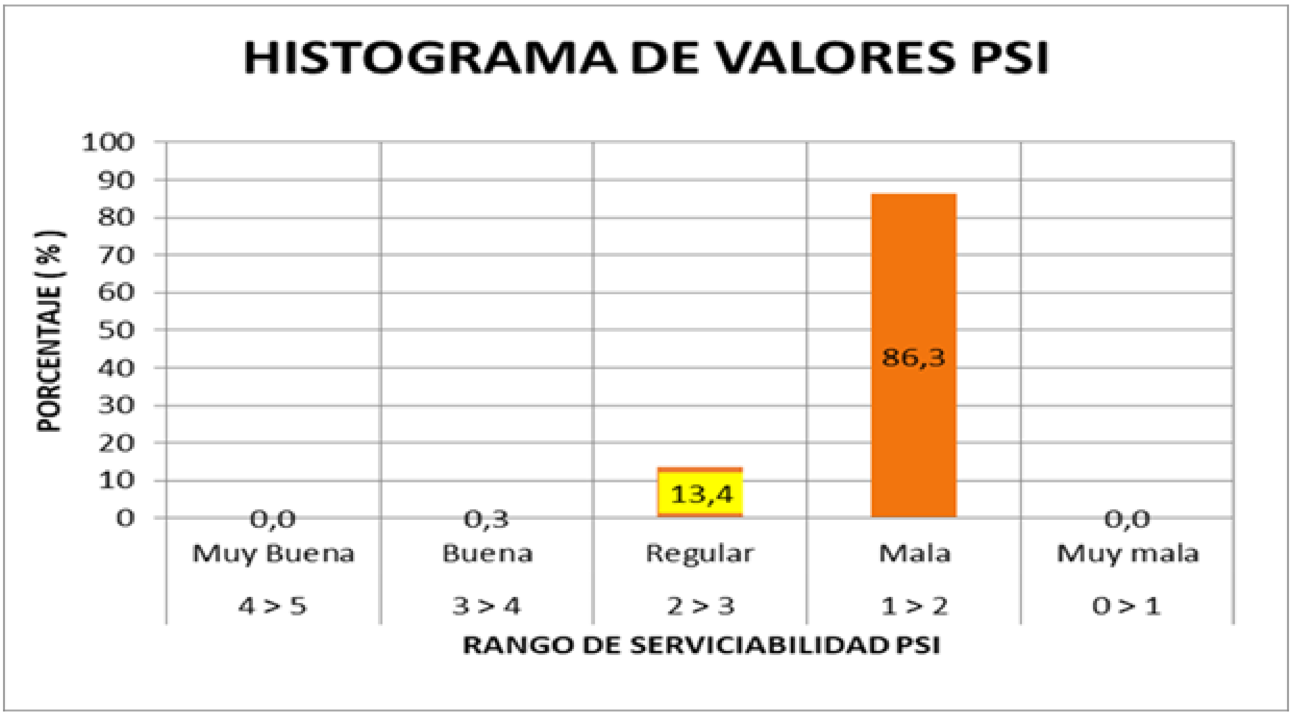

Fig. 3 Serviceability index for the Oruro-Toledo section.

Fig. 4 Coring on the Oruro-Pisiga highway

Fig. 5 shows what was described in the previous paragraph where the cracks extend internally producing a cracking in the thickness of the slab and in many areas reaching the contact with the base layer of the embankment structure, taking a representative amount in 1 km, 5 cores were extracted and the compressive strength was analyzed.

Table 1 shows the resistance of the 5 representative cores in 1 Km obtaining an average resistance of 272.8 Kg⁄cm^2 being low for the design of an international route where high tonnage vehicles travel, it can be diagnosed that in several areas where cores were not extracted because they are areas where there is contact between the wheel and the pavement, the resistance is lower, the cracks and internal fissures are of greater quantity.

The representative sclerometry is 268.6 Kg⁄cm^2, the carbonation depth identified is 4.4 with this small sample it is possible to proceed to recommend the total replacement of the slab, proposing a new high performance concrete based on furnace steel slag which is the main objective of the research for the topic "2. Aggregates/Aggregates" of the XXII Ibero-Latin American Congress of Asphalt, showing that Bolivia is prepared for technological adaptation in road engineering with the application of new materials that contribute to the world energy change and reduce environmental pollution by encapsulating the slag produced by metallurgy in Bolivia as it is an active mining territory, proposing the industrialization of a type II Portland cement.

Fig. 5 Representative core extracted from the Oruro-Toledo road.

Table 1 Compressive strength study on 1 km of the Oruro - Toledo road.

Test Date		September 9, 2022		
N°	**Password**	**Charge Kg**	**Área cm^2**	**Resistance Kg/cm^2**
1	CORE 1	25950	100	259,50
2	CORE 2	26070	100	260,70
3	CORE 3	27100	100	271,00
4	CORE 4	28500	100	285,00
5	CORE 5	28770	100	287,70
		Average		272,8

3. Research Engineering

The steel industry in Bolivia has 50 years of presence in the market, with steel construction companies and derivatives since 1969, Bolivia is a great mining country since Inca times, Pre-colonial, through the great men of tin as Simón I. Patiño, Mauricio Hochshild and Carlos Aramayo currently has mineral resources, the slag of TESA STEEL is rotary kiln that worked for more than half a century, this raw material is the slag of the rotary furnace that worked for more than half a century. Patiño, Mauricio Hochshild and Carlos Aramayo, at present it has mineral resources, the slag of ACEROS TESA is from a rotary furnace that worked for more than half a century, this raw material is the reason for research, Bolivia currently processes an approximate annual volume of 200 thousand tons of steel of which 8% is slag, Fig. 6 shows the collection of the investigated material.

According to the National Slag Association of the United States cited by [2], the slag from the Vinto locality in Oruro is black from electric arc furnaces that at the end of the steel manufacturing process the slag is the surplus in liquid and cools in dumps that need to be crushed to create a granulometry, being a residual material is outdoors so it is recommended a washing before being analyzed in laboratory as shown in Fig. 7.

Once the washing process has been completed, we proceed to crushing. For industrialization, a crusher is recommended to obtain the granulometries of the technical specifications required for the road work, complying with the quality control, the material must be analyzed in a spectrometry to know what metals it contains and what degree of toxicity it presents, Once this analysis for the dosage is concluded, it is necessary to carry out the main tests such as "Granulometry ASTM C136, Unit weight ASTM C29, Specific weight ASTM C127 ASTM C128 and Angels Machine Wear ASTM C131", which are the most used tests in Bolivia [3], as shown in Table 2.

With the results we proceeded to dose the concrete and analyze in a summarized way which design is better, if a concrete with thick slag or a concrete with fine slag, in both cases proposing a concrete that exceeds 300 Kg/cm^2 to be used for rigid pavement of considerable traffic of an international route, Fig. 8 shows the casting of specimens.

Fig. 6 Steel slag collection for concrete design.

Fig. 7 Washing the slag to be crushed and analyzed.

Table 2 Summary of studies prior to dosing.

Name		**Msc. Ing. Roger Andres Cortéz Chavez**					
Project		**Use of steel slag for rigid pavements**					
Origin		Steel TESA		Colorimetry		ASTM C40	parameter 2
Characteristics		Steel slag		free of organic matter			
Date of test		08-2022/12-2022		Standard		AAS	
Parameter	**Calcium Ca**	**Cadmium Cd**	**Chromium Cr**	**Iron Fe**	**Lead Pb**	**Magnesium Mg**	**Zinc Zn**
Units	%	%	%	%	%	%	%
L.C.	0,01	0,01	0,03	0,03	0,03	0,03	0,01
Valor	6,11	0,01	0,33	18,36	0,03	7,54	0,02
Steel slag in coarse particle size							
Test		Standard	Units	Results			
Granulometry		ASTM C136	-	M.F.	7,15	T.máx	3/4"
Unit Weight		ASTM C29	Kg/m^3	P.U.S.	1532,91	P.U.C.	1419,60
Specific weight		ASTM C127	gr/cm^3	P.E. bulk	2,76	Abortion %	1,98
Angels Machine		ASTM C131	%	Attrition		24,70	
Steel slag in fine particle size							
Test		Standard	Units	Results			
Granulometry		ASTM C136	-	M.F.	4,23	T.máx	-
Unit Weight		ASTM C29	Kg/m^3	P.U.S.	2665,00	P.U.C.	2838,00
Specific weight		ASTM C128	gr/cm^3	P.E. bulk	1,76	Absorption %	0,48
Angels Machine		ASTM C131	%	Attrition		16,20	

Fig. 8 Pouring of prismatic specimens for strength study.

3.1 Design of Concrete With Steel Slag as Coarse Aggregate

A problem that originated in the Oruro - Toledo road was the shrinkage due to the type of climate and not immediately perform the shrinkage joints, with the proposed research was implemented to combine a crushed gravel from the region of Santa Ana 5 km from the city of Oruro with crushed steel slag from Vinto in order to reach the fineness module of 7.15 that we previously stated.

The present dosage achieved to comply with the technical specifications that the road requires for its T.P.D.A. in an induced future of 20 years where the value will be of 6109 vehicles, to reach the mentioned dosage previous designs were made with the objective of observing its behavior and to be able to adjust the relation water/cement and adjustment of granulometry, the design can be improved, but initially an optimal dosage was obtained, Table 3 shows the granulometric result.

50% of slag was used in order to recycle as much as possible, thus reducing contamination and creating a granulometry that is similar or better than the Fuller model, adapting its limits to the technical specifications of the road, technically improving the test dosages, resulting in the following design shown in Table 4, where pure material is used without additives.

Table 3 Combined particle size.

<table>
<tr><th colspan="2">Granulometry</th><th>ASTM C136</th><th colspan="3" rowspan="2">Modulus of fineness</th></tr>
<tr><th>Sieve</th><th>%R C/T</th><th>% Q.P.</th></tr>
<tr><td>6"</td><td>0,00</td><td>100,00</td><td colspan="3">7,15</td></tr>
<tr><td>3"</td><td>0,00</td><td>100,00</td><td colspan="3" rowspan="2">Maxiimum size</td></tr>
<tr><td>1 1/2"</td><td>0,00</td><td>100,00</td></tr>
<tr><td>1"</td><td>5,00</td><td>95,00</td><td colspan="3">3/4"</td></tr>
<tr><td>3/4"</td><td>20,00</td><td>75,00</td><td colspan="3">Project</td></tr>
<tr><td>1/2"</td><td>45,00</td><td>30,00</td><td colspan="3">IRF WC2024</td></tr>
<tr><td>3/8"</td><td>20,00</td><td>10,00</td><td colspan="3">Ing. Roger Andres Cortéz Chavez</td></tr>
<tr><td>N°4</td><td>10,00</td><td>0,00</td><td>Date</td><td colspan="2">14/9/2022</td></tr>
<tr><td>Base</td><td>0,00</td><td>0,00</td><td>Material</td><td>G.Grushed</td><td>Slag</td></tr>
</table>

Table 4 Dosing with slag as coarse aggregate.

Data	Quantity per $1m^3$ of concrete	Relation
Water	190,00	0,41
Cement	463,41	1,00
Sand	771,79	1,66
Gravel	919,80	1,98

With the established quantities, the concrete was poured in prismatic molds to perform the ASTM C39 compression test and to break at 7 days to observe 70% of theoretical resistance, 14 days to analyze its curing and 28 days to determine the final resistance. The amount of water was reduced because the slag absorbs less water, a fact that adjusts to the energetic change by reducing the amount of this resource that is in reserve.

A concreting of 45 specimens of 15 cm of diameter by 30 cm. of height was carried out, we proceeded to the breaking of specimens where the breaks were produced in the form of well formed ends less than 25 cm. and type of crack column where the adherence of the slag to the concrete can be examined and this type of behavior is positive, because as a fictitious stone aggregate it fulfills the adherence and homogeneity in Fig. 9 we can observe the explained thing.

Table 5 shows the resistances acquired at the mentioned ages, the result was that after 7 days it already exceeds the goals of a 300 Kg/cm^2 concrete, reaching a maximum resistance of 418 Kg/cm^2, excellent resistance for implementation in Bolivia, resulting in a reduction in the amount of steel and slab thickness for repetitive loads of heavy traffic, generating a positive technological impact.

Fig. 9 Petrography of the slag with red paint to show adhesion and homogeneity.

Table 5 Acquired resistances.

Number of test tubes	Concrete Age (Days)	Average Resistance Kg/m^3
15	7	320,95
15	14	352,70
15	28	418,90

3.1.1 Statistical Study to Improve the Design

The study was conducted to analyze the probability of obtaining higher resistances with steel slag as coarse aggregate and a probability of 43.2% was obtained, indicating that the resistance can be improved with greater quality control of the materials, prolonging its useful life, proposed to have a veteran fluid transit [4], the study is shown in Fig. 10.

3.2 Design of Concrete With Steel Slag as Fine Aggregate

For the design with steel slag as fine aggregate, we proceeded with the same methodology as in the study of coarse aggregate, Table 2 specifies the above mentioned studies of the slag in fine aggregate, when working with a slag sand version, it requires more grinding to reach the required particle size, It is known that in several civil works the fine slag is added as if it were an additive in small quantities, in the research this scheme was broken for environmental reasons with a particle size that is not uniform with a fineness modulus of 4.23 combining an amount of 70% fine slag with 30% sand.

Table 6 shows the quantities required for its implementation on site with a water absorption of 0.48%, which will create a dry consistency concrete, thus reducing the use of water and, as in the previous dosage, the amount of slag used reduces contamination by pretending to be encapsulated in important road works and innovating its use in Bolivia so that it can be standardized and studied in greater depth in the future.

The concreting for 45 specimens whose objective is to exceed the resistance of 300 Kg/cm^2, proceeded to the breakage of 7,14 and 28 days of age to study the evolution of the resistance with the laboratory care required by the ASTM C39 standard, in Table 7 the proposed design is examined, and the concrete reaches its final resistance with 310 Kg/cm^2 surpassing the objective.

The types of breakage are column type, diagonal fracture and well formed cone at one end of the edge of the specimen, being able to determine that it is a compact concrete and good for the design of rigid pavement, surpassing the old pavement that is currently in service, in Fig. 11 it can be clearly observed the homogeneity and adherence, optimal for use in road works.

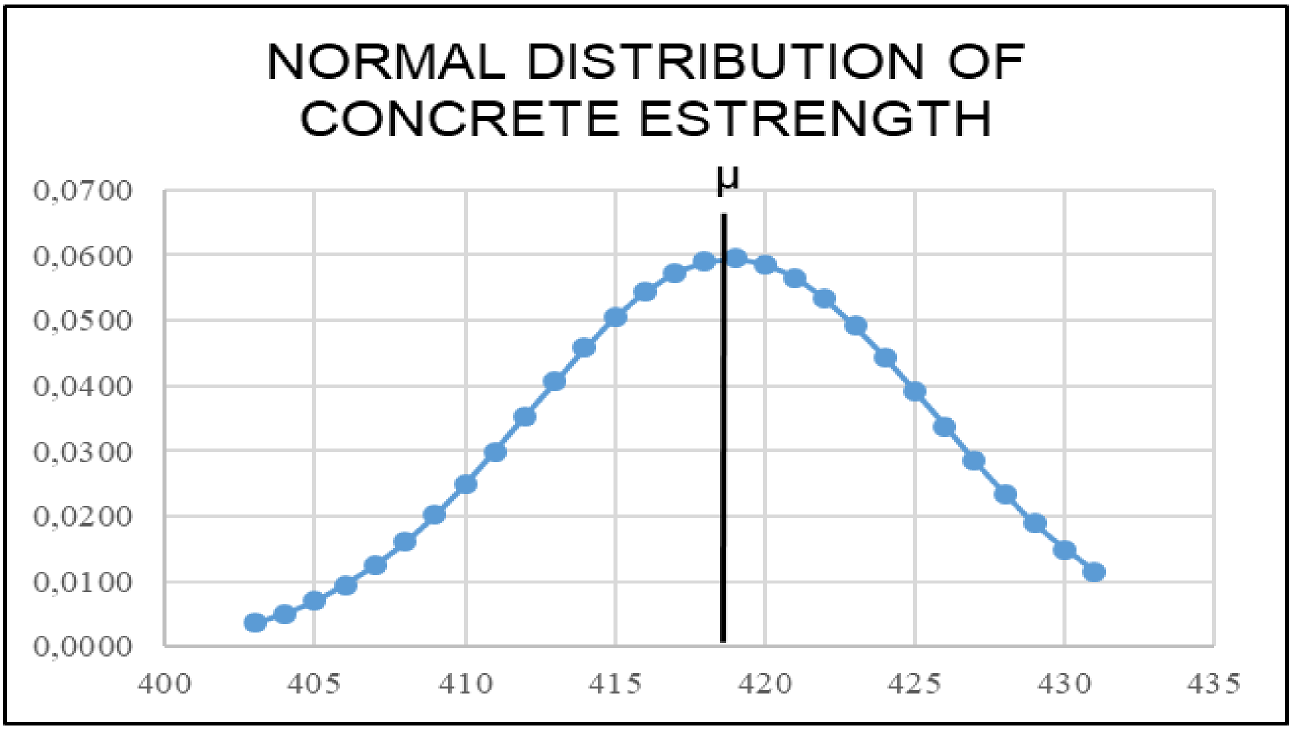

Fig. 10 Probability of improving a strength with steel slag as coarse aggregate.

Table 6 Dosage with slag as fine aggregate.

Data	Quantity per $1m^3$ of concrete	Relation
Water	190,00	0,41
Cement	463,41	1,00
Sand	982,63	2,12
Gravel	708,96	1,53

Table 7 Acquired resistances.

Number of test tubes	Concrete Age (Days)	Average Resistance Kg/m^3
15	7	242,05
15	14	269,45
15	28	311,60

Fig. 11 Petrography of the slag (black dots) to show adherence and homogeneity.

3.2.1 Statistical Study to Improve the Design

A second study was carried out to find the probability of improving the resistance of 420 Kg/cm^2 with steel slag as fine aggregate, the result of the probability of improvement is 0% because the objective of the previous dosage was not reached, but the proposed 300 Kg/cm^2 was reached, as mentioned the slag used as fine aggregate is very delicate as it is a glassy material in massive quantity and adequate results are not obtained. In investigations of previous civil works, suitable results are observed when combining the molecular chemistry of the materials, the slag should be used as dust with particles smaller than the N°200 sieve, in quantities that do not exceed 10% of the total fine aggregate so that molecularly the slag replaces the air molecules left by the water when converting from liquid to gaseous state, the percentage can vary by the type of slag [4], the probability studied is shown in Fig. 12.

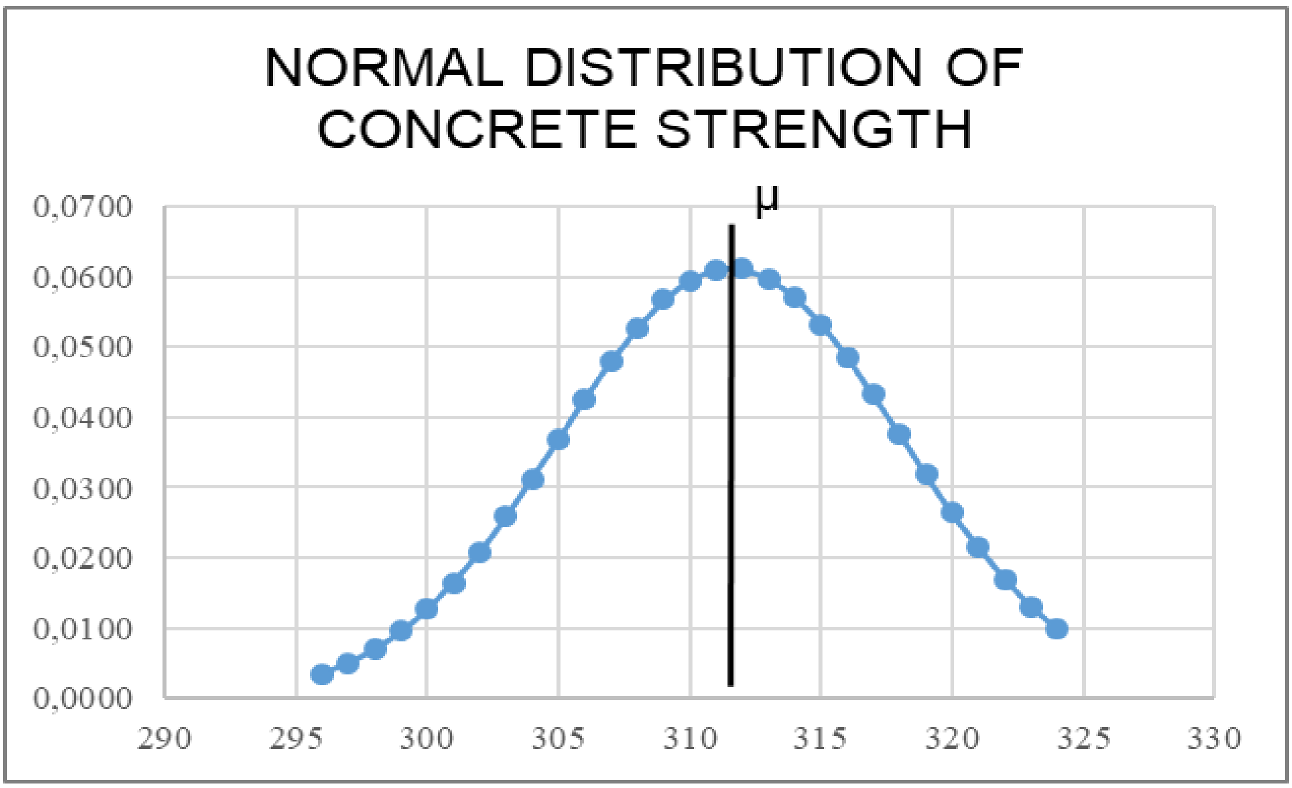

Fig. 12 Probability of improving a strength with steel slag as fine aggregate.

3.3 Comparative Analysis of Scientific Research

Based on the study of compressive strength and the study of strength improvement through the probability between the dosage with steel slag as coarse aggregate and the dosage with steel slag as fine aggregate, the slag as coarse aggregate was found to meet the technical specifications for the placement of roads with rigid pavement in the region of Oruro - Bolivia [5], with this choice, the application of the design with coarse-grained steel slag in the construction of an experimental slab was carried out.

3.4 Application of the Design On Site

Fig. 13 shows the concreting of a slab with the dosage with coarse-grained steel slag.

In Fig. 14 you can evaluate the petrography of the aggregates precisely of the thick slag that is marked in green circles and some of them shine with the light

Fig. 13 Application and pouring of slab with steel slag as coarse aggregate.

Fig. 14 Cores extracted for visual and strength analysis.

Fig. 15 Application Core Compression Test.

showing part of the metals they contain, starting the creation of a brand new IRON-CONCRETE for Bolivia therefore innovating technologically in the world of roads and in turn reducing environmental pollution using a recycled material.

In the compressive strength test shown in Fig. 15, the result of the core is 430 Kg/cm^2 adequate for a road of considerable traffic as it is international with heavy transport, with this result a slab of less thickness and less amount of reinforcing steel can be designed, complying with the XXII Iberolatinoamerican Asphalt Congress presenting a research for the topic "2. Aggregates/aggregates" for being an innovative material in Bolivia.

4. Outcome of Scientific Research

The present research intends to be applied to road works, mainly in the Oruro - Toledo highway, since it is old and deteriorated, it needs a total replacement of the slab, so incorporating an innovative material that contributes to the environment in its elaboration is very important to enter the stage of technological adaptation and energy change in Bolivia, in such a way that it is also an incentive to encourage future research and use new materials for pavements in general and regulate them in their application in the future.

4.1 Conclusions

It is concluded that steel slag is a suitable material for the construction of rigid pavements in frigid areas such as the Bolivian Altiplano, either as coarse aggregate or fine aggregate, generating high resistance in the concrete, at the same time it is suitable for tropical areas because the slag requires high temperatures to melt.

4.2 Recommendations

It is recommended to carry out more in-depth studies to refine resistance such as molecular chemical analysis, long-term deterioration, analyze the behavior of steel slag from Vinto (ACEROS TESA) as dust for higher quality designs, due to the amount of cement used, it is also advisable to encourage Bolivia to industrialize a type II Portland cement that has steel slag as raw material.

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