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FIRE RESISTANCE AND HEAT TRANSMISSION PROPERTIES OF CONCRETE AND MASONRY MADE WITH BLAST FURNCE SLAG AGGREGATE

Blast furnace slag is generally recognized to have exceptionally high fire resistance. Occasionally, however, it is necessary to know specifically how much better it is for certain applications, and in some instances proof of the excellence of blast furnace slag is requested by potential users. The purpose of this document is to provide factual information in support of the high fire resistance rating of blast furnace slag, and to indicate the savings which can result from its use.

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PART I GENERAL INFORMATION

The fire resistance of cement concrete or concrete masonry is dependent upon many factors. Two of the most important of these, however, are the heat transmission and structural characteristics of the aggregate used[1]. The contribution of low heat transfer to fire resistance is obvious. The contribution of structural characteristics may need explanation.

Numerous investigations have proven conclusively that the moisture content, or relative humidity, of concrete or masonry has a significant effect on fire resistance - the higher the moisture content the greater the fire resistance. Tests by the Portland Cement Association Fire Laboratory have indicated that moisture equilibrium is reached in a structure at about 70-75% relative humidity. Other tests have shown that a 70% relative humidity is a good year-around average for nearly all parts of the United States. The effectiveness of this relative humidity is in turn dependent upon both the voids in the concrete and the voids (absorption) in the aggregate. Blast furnace slag is superior to natural aggregates with respect to these important physical characteristics because of its vesicular (non-inter connected) cellular structure and higher absorption rate.

Another uniquely favorable characteristic of slag when it is used in reinforced concrete is that its coefficient of expansion is essentially the same as that of reinforcing steel. Thus, when temperatures increase in a reinforced structure the steel and concrete expand at about the same rate avoiding internal stresses and strains which could be created by differential expansion. Slag is the only commonly used aggregate that will, either alone or in concrete, produce a uniform expansion over the entire range of temperatures from atmospheric to those encountered in severe fires and fire tests (2000ºF+).

The relative fire rating of various aggregates is translated into practical and usable terms through the testing and rating of various Agencies in three principal fields: (1), fire testing by the Underwriters' Laboratories, Portland Cement Association, Fire Prevention Research Institute, National Bureau of Standards, National Research Council of Canada and other similar organizations; (2), certification service by the Underwriters' Laboratories of Chicago and Canada; and (3), recommended fire ratings by American Insurance Association, National Bureau of Standards and National Fire Prevention Association.

Fire rating testing in the United States and Canada is accomplished in accordance with Standard Methods of Fire Tests of Building Construction and Materials, ASTM designation E119. This test determines the comparative fire resistance of materials and assemblies and results in a rating expressed in terms of time a construction element will resist a specified heat application without causing temperature rises at designated points to exceed specified levels, and without resulting in structural changes in excess of designated limitations.

Certification service and recommended fire ratings are based upon these fire tests. Certification, or "label service, provides a degree of guarantee that a unit or assembly, constructed to stipulated specifications within close tolerances, will have a specified fire resistance. This certification service is usually limited to prestressed concrete and masonry units.

Recommended fire ratings are developed from an analysis of fire tests, and are usually published in the form of handbooks or pamphlets. Perhaps the one most widely used is that of the American Insurance Association. Ratings are expressed in terms of hours and minutes that a specified unit or thickness will resist standard fire tests, or the "equivalent thickness" required of a wall constructed of cored (masonry) units to obtain a specified fire resistance expressed in hours. The term "equivalent thickness" is used only with concrete masonry and is determined by dividing the solid volume of a unit by its face area. It is a computation to determine what the thickness of the unit would be if the hollow-core was eliminated and the block compressed to a solid unit.

Factual data concerning the fire tests made on various types of construction using blast furnace slag, and other aggregates; and other data pertaining to heat transmission are provided in Part II of this publication. The superiority of blast furnace slag for structures requiring good fire or heat resistance is clearly shown by this data.

PART II - *TEST RESULTS AND OTHER FACTUAL DATA*

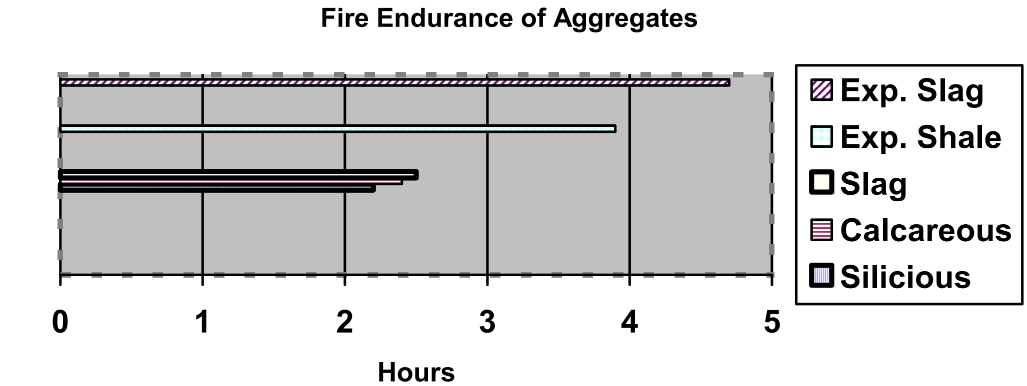
Fire Resistance of Reinforced Concrete Slabs

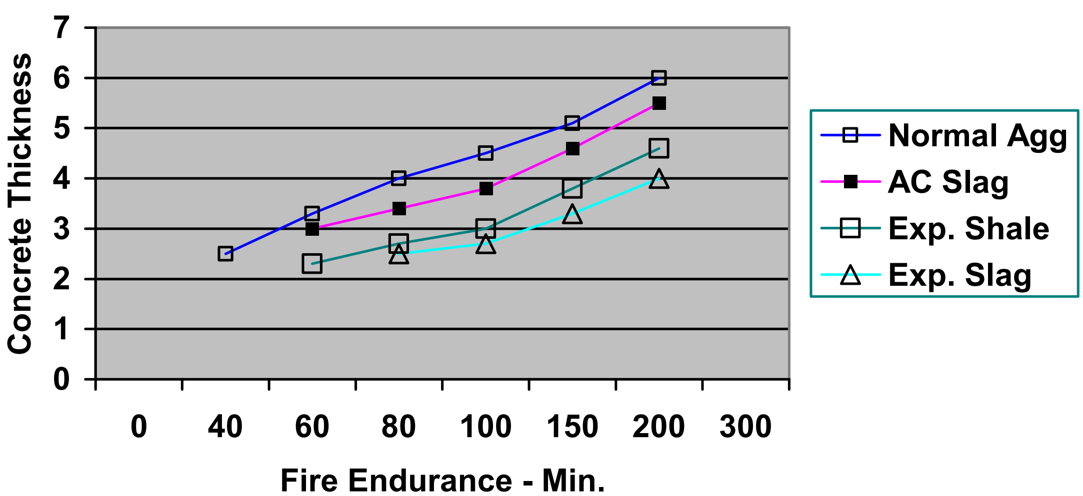
The following fire resistance ratings for reinforced concrete slabs with several types of aggregates are shown in a document of the American Insurance Association, formerly the National Board of Fire Underwriters, entitled; "Fire Resistance Ratings" [2], pp 46 and 47.

Aggregate	Slab Thickness, Inches	Protection to steel, Inches	Fire Rating, Hours
Air-cooled Slag	6	1	4
Traprock) Calcareous) Siliceous)	6	1	3
Limestone*	6	1	3
*Slab also contained electrical raceways and junction boxes			
Air-cooled Slag	4 3/4	3/4	2 1/2
Traprock) Siliceous Gravel)	4 3/4	3/4	2
Limestone or) Calcareous Gravel)	4 3/4	1	2
Expanded Slag	4 1/2	3/4	4
Expanded Shale	5 1/4	3/4	4

These ratings are based on tests conducted by the Underwriters' Laboratories, Inc.[3]. They clearly demonstrate improved fire resistance for reinforced concrete slabs with slag as compared to both normal and lightweight natural aggregates.

I. A. Benjamin reported on the fire resistance of various types of aggregates in a paper for the American Concrete Institute[4]. Graphs from his paper reproduced below depict the superiority of slag.





Fire Resistance of Prestressed Concrete Shapes

In the summer of 1971 the Underwriters' Laboratory conducted its standard fire resistance evaluation test on 8" Corefloor slabs made with slag coarse aggregate and natural sand. These units were made by the Spiroll process and 6" augers (cores) were used. A standard slab made of these Corefloor units withstood the heat application for 2 hours without exceeding the allowable temperature rise on the unexposed surface. The assembly prevented the passage of flame, carried the live load, and remained in tact for 4 hours and 4 minutes after which the furnace fire was extinguished.

Based upon these tests the UL will certify 2 hour fire rating for an 8" Corefloor slab using 6” augers. As a result of an engineering study the UL also determined that 3 and 4 hour classifications could be obtained with these 8" units by adding a topping thickness of non-structural concrete of 1-1/4 inches and 2 inches respectively, without affecting the prestressing strands for these units.

Previous UL testing had determined that 8" Coref1oor slabs with a 5-1/2 inch auger using stone and gravel, would provide a 2 hour rating. Analysis of that test and of the slag test cited above has determined that a 2 hour rating with 6 inch augers cannot be extended to gravel and stone concrete based upon the time at which the assemblies reached their limiting temperature end points and equivalent thickness difference between the units.

Detailed information on the UL test is contained in UL report dated August 23,1971[5].

Fire Resistance of Concrete Columns

The known fire tests on concrete columns with various aggregates are more difficult to evaluate than the data cited previously, however, the table below shows some results of such tests conducted by the National Bureau of Standards which are typical (tests on columns made with siliceous gravels failed under the working load in less than four hours and are not included in this tabulation.)

Spirally and Vertically Reinforced Concrete Columns

(Outside diameter, 18 inches. Thickness of concrete outside the steel, 1-1/2 inches. Reinforcement: 2 per cent vertical, 8 round rods, 3/4 inch diameter; 1 per cent spiral, 5/16 inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load 141,000 pounds = 822 lbs./in.^{2}).

				Stress at Maximum Load			Maximum Temperature at End of Fire Test		
Aggregate	Column	Age at Time of Test		Without Fire Test:	At end of 4-hour Fire Test	Tested cold after 4-hour Fire Test	At Depth of Vertical Rods	Midway between steel and Center	At Center of Column
Elgin (Ill.)	85	4	1	--	--	4,440	480	--	--
gravel & sand	86	4	1	--	--	5,240	520	--	--
	87	4	4	5,620	--	--	--	--	--
W. Winfield (Pa.)	17	7	1	--	--	4,770	520	240	120
Limestone &	18	8	17	--	--	5,320	560	180	100
Pittsburgh sand	20	7	4	6,890	--	--	--	--	--
Blast-furnace slag	48	4	0	--	--	--	480	85	85
& Pittsburgh	49	4	7	--	2,700	--	--	--	--
sand	50	4	21	4,870	2,260	--	465	110	100
New Jersey trap	54	4	7	--	2,420	--	610	190	100
rock and Pittsburgh sand	55	4	16	--	3,000	--	560	239	110

The results indicate that the slag concrete did an excellent job of keeping internal temperature rise to a minimum. Tested to failure while hot at the end of 4 hours fire exposure, the columns still carried about 3 times their design working load. It will be noted that the Elgin (calcareous) gravel and limestone columns had higher initial strengths and were tested cold after the fire tests.

In arriving at "fire endurance ratings" based on these tests, a complicated formula was used which included strengths at the end of test, but completely ignored any factors of initial strength level, age, and effects of hot vs. cold tests at the end. As a result, both the slag and traprock were penalized as compared to the limestone and calcareous gravel. It is believed however, that the actual data indicate the blast furnace slag to have performed better than any of the other aggregates.

Fire Tests on Expanded Slag Floor Concrete

In 1960 the Underwriters Laboratory of Canada[7] conducted a fire test of floor and ceiling construction consisting of steel floor units with an expanded slag poured concrete topping and supported by a sprayed fiber protected beam. The tests were conducted in accordance with ASTM Procedure E119. The results of this test are published as Design No. C 108 - 3 HR (Beam 1-1/2 Hr) in ULC Building Construction, Vol. 2, September 1968.

The slag concrete consisted of 590 pounds Portland cement, 570 pounds expanded coarse slag, 1070 pounds expanded fine slag, 275 pounds fine sand, 480 pounds of water, 2.96 ounces Darex. The mix had a slump between 1 and 2 inches and contained 7% air. The average 28 day compressive strength was 3456 psi.

The temperature on the unexposed side of the floor assembly did not exceed the permissible average rise of 250 F and none of the individual floor thermacouples showed a rise in excess of the allowable 325 F during the 3 hour fire exposure.

Based upon these tests inspection service on steel floor units with fire ratings from 2 to 4 hours were authorized, depending upon the construction design.

Fire Tests on Concrete Deck Made with Precast Expanded Slag Cored Slabs made by the Flexicore Process.

These tests were conducted by the National Bureau of Standards[8] using ASTM E 119 fire test procedures on a 17‘ 10" x 13’ 4” slab made up of precast hollow core units 4" deep, 24” wide, and 17' 10” long. Three full length, oval cross-section cores 2" deep and 5-1/2" - 6" wide were formed in each unit. Each unit , as reinforced with six 5/16" and two 1/2" longitudinal non-deformed steel bars, 4 on top and 4 on bottom, with 1” average cover. The Flexicore units were covered with a 1-5/8" thick topping of expanded slag concrete. Throughout the test the specimen was subjected to a total load of 111 lbs/ft^2 to stress the extreme fibers of the reinforcing bars to 20,000 psi.

A fire endurance rating of 4 hr. 2 min. was obtained with the limit being determined by the average temperature rise on the unexposed surface of the slab.

Fire Resistance of Concrete Masonry Walls

A comparison of air-cooled slag and other aggregates in their effect on the fire endurance of concrete masonry walls is provided by tests of the Portland Cement Association. Comparative data from these studies, reported by Menzel[9] are shown in the following table:

**Fire Endurance of Walls As Affected by Character of Aggregates
(Walls 8-inch thick made with 3-core block)**

Test No.	Aggregate			Mix by Volume	Cement Content - # per Block	Avg. air-dry Weight – #/ft² of wall	Fire Endurance period - minute	
	Type	F. M.	Weight - #/ft³*				wall	Per#/ft²
101	Siliceous Gravel A	3.50	115	1-7.5	4.31	53.5	124	2.32
22	Siliceous Gravel B	3.70	113	1-8.3	4.18	54.9	129	2.35
106	Crushed Fire Brick	3.50	91	1-7.5	4.29	44.2	145	3.28
8	Calcareous Gravel	3.50	120	1-7.8	4.20	54.8	150	2.74
65	Crushed Limestone	3.50	120	1-7.9	4.33	57.3	158	2.76
108	Air-Cooled Slag	3.50	102	1-7.5	4.25	48.9	193	3.95

*Based on dry rodded 0 to 3/8-inch aggregate graded to fineness modulus indicated

The aggregate types have been arranged in order of increasing fire resistance. The siliceous gravels have the least fire endurance, followed by the crushed brick, calcareous gravel and limestone, and the air-cooled slag. The slag is shown to have significantly better fire resistance than do any of the others, on the basis of either the total fire endurance period or the fire endurance per lb. per sq. ft. of wall.

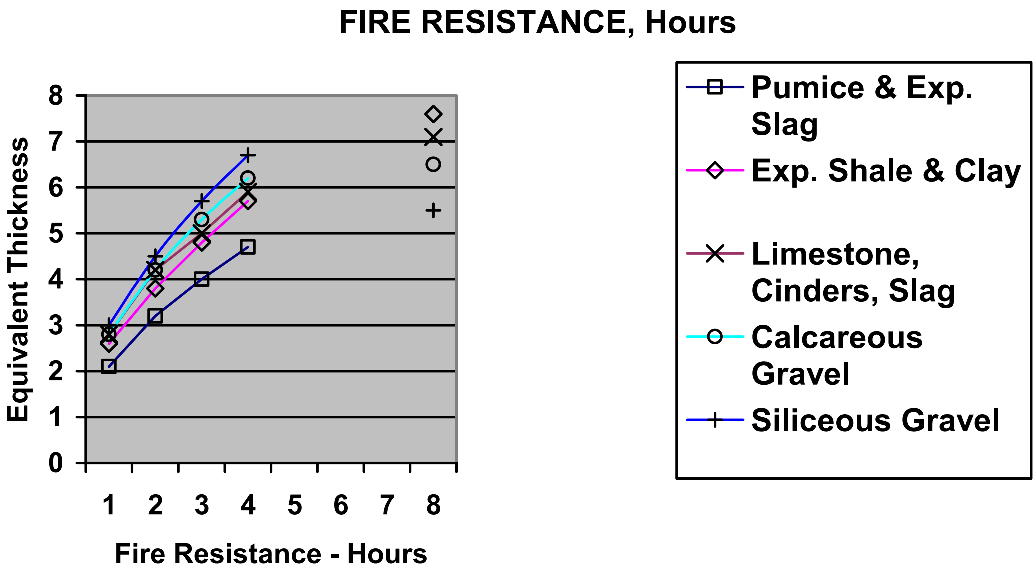
These test results follow exactly the same pattern as do the Underwriters' Laboratories, Inc. tests on reinforced concrete slabs: for equivalent designs the air-cooled slag provides better fire resistance than do the natural aggregates.

The American Insurance Association (successor to the National Board of Fire Underwriters) has over the years collected data on many tests on masonry units using various types of aggregates and mixes. Based upon these tests they have published a tabulation of estimated ratings of concrete masonry unit walls and partitions as follows (2) - (page 115 March 1970):

WALLS AND PARTITIONS

	Concrete Masonry Units Estimated Ratings	Members Framed in Wall: None or Noncombustible — Minimum Equivalent Thickness Inches, for Ratings of :			
		4 hrs.	3 hrs.	2 hrs.	1 hr.
Unlisted Units	Coarse aggregate, expanded slag, or pumice.	4.7	4.0	3.2	2.1
	Coarse aggregate, expanded clay or shale.	5.7	4.8	3.8	2. 6
	Coarse aggregate, limestone, cinders or unexpanded slag.	5.9	5.0	4.0	2.7
	Coarse aggregate, calcareous gravel.	6.2	5.3	4.2	2.8
	Coarse aggregate, siliceous gravel	6.7	5.7	4.5	3.0

This data has been converted to graphic format by Copeland (10) as follows:



In 1966 full scale ASTM fire tests were performed on various types of masonry units by the Fire Test Sections of the Canadian National Research Council. Based upon these tests a Canadian code shown below has been published.[11] This code shows that slag is far more fire resistant than natural aggregates for all periods of fire resistance ratings.

Minimum Thickness of Masonry Walls, Load Bearing & Non Load Bearing

	Minimum Thickness in Inches for Fire Resistance Ratings of:						
	½ hr	¾ hr	1hr	1½ hr	2 hr	3hr	4hr
Concrete Masonry Units, Solid or Hollow, & Monolithic Concrete Type S* Concrete Equivalent Thickness	2.8	3.2	3.7	4.6	5.5	6.7	8.0
Type N* Concrete Equivalent Thickness	2.5	3.0	3.5	4.3	5.0	6.0	7.0
Type L* Concrete Equivalent Thickness	1.7	2.2	2.7	3.3	4.0	4.8	5.7

*Type S coarse aggregate is 30-65% siliceous
*Type N not more than 30% of the coarse aggregate is siliceous
*Type L all of the aggregate is either expanded slag, expanded clay, expanded shale or pumice.

Fire Tests of H Section Steel Column Protected with Slag Concrete Masonry Units[12]

In January 1963, a nationally recognized independent Canadian Research Agency, conducted a fire test on a 6'1 steel H section column protected with 3-5/8" thick solid expanded slag masonry units using ASTM test procedure E119-61. The column was judged to have failed when the average temperature of 3 thermocouples at anyone of four temperature recording levels on the steel column exceeded l000°F or the temperature of anyone of the measuring points exceeded l200ºF. The 1000º limit was reached first after 4 hours and 25 minutes; the l200º limit was not reached until the termination of the test at 4 hours and 39 minutes.

British Evaluation of Slag as a Fire Resistant Aggregate

Details of the fire tests and investigations of building fires carried out in England are not readily available. However, even a brief check on British references to blast furnace slag illustrates the high regard which it has for this purpose. Davey and Ashton (l3) state:

> "The classification of aggregates in descending order of merit for the fire resistance of the concrete made from them is as follows:
>
> "Class 1 (a) Foamed slag, pumice.
> "Class 1 (b) Blast furnace slag, crushed brick and burnt clay products, well burnt
> “Class 2 Siliceous aggregates generally", e.g. flint, gravel, granite and all crushed natural stones other than limestone."

Thus the air-cooled slag appears to be considered the equivalent or better than all aggregates except foamed (or expanded) slag and pumice. F. M. Lee[14] in his well known text and reference, “The Chemistry of Cement and Concrete" discuses the effects of various normal weight aggregates on fire resistance and concludes: "In actual fire tests it has been found that dense limestones form good fire-resistant aggregates . . . . The most resistant of all concretes to fire are probably those made with a blast furnace slag aggregate. This has been shown by both small-scale laboratory experiments and large.-scale tests on structure."

The British specifications for slag aggregate[15] also point out the advantages of slag in fire-resistant concrete: “Amongst the heavy aggregates, crushed dense burnt clay bricks have usually been considered to produce the most fire-resistant concretes, but slag aggregates show properties very similar to those of the crushed brick."

Thermal Conductivity of Concrete

Although available thermal conductivity tests have been conducted at relatively low temperatures, the results are of interest in that they reveal some of the characteristics of concretes made with different aggregates and exposed to heat. Foxhall [16] presents data showing lower ***k*** values for expanded slag concretes than for those using other structural lightweight aggregates. Lewis[17] reports later tests on expanded slags that confirm and extend Foxhall's data and show a straight line relationship between unit weight and ***k*** value, from about 1.8 at 70 Ibs./cu. ft. to 3.2 at 105 lbs./cu. ft. Corresponding ***k*** for expanded clay concrete having the same unit weights (from Foxhall) would be 2.5 and 4.5.

Various test results on heavy or normal weight concretes show considerable variation. The ASHVE[18] reports ***k*** values of 5.3 to 5.9 for air- cooled slag concrete, compared with 10.8 to 16.4 for limestone and gravel concretes. Unit weights of the slag concretes were reported to be 124-125 Ibs./cu. ft., while that of the natural aggregate concretes were over 130 Ibs./cu. ft. British tests[19] report ***k*** values of 7.2 for slag concrete and 10.0 for gravel with unit weights of 145 and 140 Ibs./cu. ft. respectively. “No fines" mixes with the same two aggregates gave values of k = 4.4 for slag at 120 Ibs./cu. ft. and 6.5 for gravel at 115 1bs./cu. ft.

Thus the available data show that, for the entire range of concrete unit weights, whether with lightweight or normal weight aggregates, blast furnace slag produces lower thermal transmission values than do other aggregates. The lesser rate of heat transfer through slag concrete probably is a factor in its superior fire resistance.

Coefficient of Thermal Expansion

Another factor in aggregate and concrete characteristics that affects fire resistance is the coefficient of thermal expansion. Even in low temperature ranges, natural aggregates vary widely in coefficient of expansion. Thus Griffith[20] lists linear coefficient of thermal expansion varying from 1.7 to 6.8 x 10^{-6} per ºF for limestones and dolomites and from 1.9 to 6.6 for granitoid rocks. Cherts and quartzites were more consistently high, ranging from 5.5 to 6.7 x 10-. In addition, some minerals, such as calcite, expand differently in different crystallographic directions, and rocks may have irregular thermal expansion curves even at relatively low temperatures[21].

The coefficient of expansion of Portland cement paste is higher than that of aggregates.[22,23] The effect of any aggregate in mortar or concrete is, therefore, to decrease the expansion. The amount of reduction and the final coefficient of expansion of the concrete is dependent upon the coefficient of expansion of the aggregate.

Tests of various aggregates by Verbeck and Hass[24] show that blast furnace slag has a coefficient of expansion intermediate between the high values obtained for some siliceous aggregates and the generally lower values exhibited by some calcareous materials and igneous rocks. Bonnell and Harper report tests in England that correlate the aggregate coefficients with those of the concrete and show blast furnace slag to be intermediate in value, about halfway between the extremes obtained. [22 - p. 7] Results of some of their tests on 1:6 concrete mixes are as follows:

Thermal Expansion (per ºF)

Aggregate	Air Storage (3 months)	Wet Storage (3 months)
Gravel	7.3	6.8
Granite	5.3	4.8
Quartzite	7.1	6.8
Dolomite	5.3	4.7
Sandstone	6.5	5.6
Limestone	4.1	3.4
Portland Stone	4.1	3.4
Blast Furnace Slag	5.9	5.1

The potential benefits of such an intermediate thermal expansion value becomes apparent when one considers the effects of very high or low values. At elevated temperatures, high coefficients of expansion produce large dimensional changes, excessive warping under non-uniform heating conditions and high stresses in restrained sections which may be very detrimental structurally. Very low coefficients of expansion for concrete indicate wide discrepancies between aggregate and cement paste, leading to large internal stresses under temperature changes and the possibility of cracking and strength loss. Concretes having intermediate values would be logically expected to have some advantages under high temperatures.

When concrete temperatures are elevated to those encountered in building fires and fire tests, other aggregate characteristics influence the results. Lea[14] describes these effects as follows (temperatures cited are in degree Centigrade):

> "In mortars and concretes the aggregates present undergo a progressive expansion on heating while the set cement, beyond the point of maximum expansion, shrinks. These two opposing actions progressively weaken and crack the concrete. The various aggregates used in concrete differ considerably in their behavior on heating. Quartz, the principal mineral constituent of sands and most gravels and a major constituent of the acid igneous rocks, expands steadily up to 573º. At this temperature it undergoes a sudden expansion of 0.85 per cent, due to the transformation of 'low' quartz to 'high' quartz. This expansion has a disruptive action on any concrete in which quartz forms an aggregate."
>
> ". . . Limestones expand steadily until a temperature of about 900º is reached and then begin to contract owing to decomposition with liberation of carbon dioxide."

Blast furnace slag contains no quartz, calcite or dolomite which are characteristic constituents of igneous and calcareous rocks. Therefore, no sudden and detrimental changes in coefficient of expansion of the slag or slag concrete would be expected. That there are, in fact, no such effects with blast furnace slag is shown by the work of Endell in Germany[25], who determined length changes in both aggregates and Portland cement mortars up to 12000C (22000 F), using blast furnace slag, granites, sandstones, limestones, basalt, diabase, broken brick and copper slag. Of all the aggregates tested only the blast furnace slag showed a uniform expansion up to 1200 F and remained unaffected in any other way. Similar results were obtained with 1:3 mortars: the smallest and only uniform volume change was exhibited by the mortar containing blast furnace slag. These results led Endell to the conclusion that blast furnace slag was far superior to the other aggregates in concrete for high temperature use.

Uniform coefficients of expansion were also shown by two slags tested by the National Bureau of Standards[26] up to the maximum temperature used of l840º F. Studies in England[27] led to the conclusion that, "Blast furnace slag aggregates in general are unaffected by temperatures below about 1200º F."

It seems evident that the uniform coefficient of expansion characteristics and. lack of minerals that produce erratic effects When exposed to high temperatures would logically be expected to provide superior performance for blast furnace slag as compared to other normal weight aggregates in concrete exposed to high temperature.

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