Energy absorption potential of light weight concrete floors

Robert M. Korol and K.S. Sivakumaran

Abstract: This paper investigates the energy absorption potential offered by light weight concrete (LWC) floors, perhaps when a building is poised to collapse from some extreme loading event. It is assumed here that the failure of LWC structural floor slabs would likely result in both break-up and pulverization of the concrete. To estimate the extent to which crushing of large portions of floor slab material would absorb energy, a series of concrete penetration tests employing patch loading was undertaken on scaled down model slabs. Six specimens had free (unconfined) edges, while the other four were confined along the edges. The test results, together with research findings obtained from the mining and milling industry, indicate that such floor systems would likely play an important role in absorbing energy during global collapse catastrophes.

Key words: energy absorption, experimental, light weight concrete, penetration tests, patch load, sieve analysis.

Résumé : Le présent article étudie le potentiel d'absorption d'énergie offert par les planchers en béton léger, par exemple lorsqu'un immeuble pourrait s'effondrer lors d'un événement de charge extrême. Nous présumons que la défaillance des dalles de plancher en béton léger pourrait probablement découlerait probablement à la fois d'une cassure et d'une pulvérisation du béton. Afin d'estimer la portée de l'écrasement de grandes portions du matériel de la dalle de plancher pourrait absorber de l'énergie, une série d'essais de pénétration du béton utilisant le chargement ponctuel a été entreprise sur des dalles à échelle réduite. Six échantillons présentaient des rebords libres (non confinés) et quatre autres étaient confinés le long des rebords. Les résultats des essais, ajoutés aux conclusions de la recherche obtenues de l'industrie des mines et du traitement des minerais, indiquent que de tels systèmes de plancher pourraient probablement jouer un rôle important dans l'absorption d'énergie lors de catastrophes d'effondrement global.

Mots-clés : absorption d'énergie, expérimental, béton léger, essais de pénétration, chargement ponctuel, analyse par tamisage.

[Traduit par la Rédaction]

Introduction

Very little attention has been given in the structural engineering field to post-failure response offered by floors, beams, and columns that transfer an array of loads to the structural framing system and to the foundation. Minimizing dead load is certainly of benefit in high-rise building construction, and for this reason steel structures are often built with light weight concrete (LWC) floor systems. It is of interest, therefore, to examine whether LWC, comprised of blast furnace slag aggregate also has virtue in providing energy absorption potential in mitigating a global collapse event. One aspect to such an event is the possibility of an upper floor collapsing onto the one immediately below and whether there is a simple model that can be proposed that would take into account the resistance offered by the lower floor. A critical consideration in such a scenario is the question of energy expended during a conceived gravity driven front, when main upper floor systems collide with the surfaces below. We might well imagine the flange of a floor beam striking a light weight concrete floor in a localized area, penetrating its surface and causing localized pulverization. Depending on how many hard elements are involved would indicate the extent to which the impacted floor offers a brake on the motion continuing. Needless to say, the columns would generally be expected to provide the bulk of the resistance needed in preventing global collapse, however, the integrity of some floor-to-column connections could be jeopardized in extreme event cases. In such a circumstance, the floor systems might just provide a degree of resistance and energy absorption that could mitigate the worst case outcome for a structure and its occupants. A brief description is given below of empirical studies pertinent to our attempt to shed light on the subject being addressed.

Received 1 December 2011. Revision accepted 17 September 2012. Published at www.nrcresearchpress.com/cjce on 17 October 2012.

R.M. Korol and K.S. Sivakumaran. Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L7, Canada.

Corresponding author: K.S. Sivakumaran (e-mail: siva@McMaster.ca).

Written discussion of this article is welcomed and will be received by the Editor until 31 March 2013.

Energy models for construction materials

The estimation of energy required for a given size reduction, such as converting a slab of concrete into dust, has evolved over a long period of time. Indeed, to ascertain the amount of energy associated with pulverizing materials is an inexact science at best, especially when the composition consists of a mix of minerals that are of random size, shape, spacial position and are non-homogeneous. Concrete is just such a material, and its comminution properties are, hitherto, largely beyond the interests of the structural engineer. However, it is important in circumstances such as in building subjected to impact or blast loading, that we aim for a reasonable estimate of a structural material's ability to absorb energy while undergoing a failure condition beyond its ultimate load carrying state.

Historically, milling of minerals has played an important role in the recovery of metals and industrial minerals for many centuries, while methods of analysis appear to have had their origins much later. One of the first was research done in Germany by Von Rittinger (1867) on the processing of aggregates in which he ascertained that the energy required for size reduction was directly proportional to the change in the surface areas of the particles comminuted. Some years later, Kick (1885) suggested that particle size itself was the crucial parameter that determined the amount of energy needed to break down materials possessing brittleness properties. The difference in the two theories comes down to the value of the constant n in the equation $dE/dx = Kx^n$, where dE is the differential energy required in the comminution process, x is a typical particle length dimension, dx its change, and K is a constant pertinent to the material's resistance to pulverization. If adhering to Kick's Law, n has the value of –1, while in Rittinger's case, $n = -2$. According to Holdich (2003), Kick's Law is a reasonable measure for reducing the size of coarse particles, whereas Rittinger's equation is more appropriate for comminuting fine particles.

It was not until the middle of the 20th century that others proposed alternative formulations for prescribing energy requirements in such processes. Indeed, researchers such as Bond (1952), Schuhmann (1960), and Fuerstenau and Somasundaran (1965) laid the framework for much of modern comminution theory that is still being used today in various industries that utilize crushing, grinding, and milling — thus providing important products for use in present day society. In essence, the expression that Bond (1952) proposed is the integrated equivalent of the $dE/dx = Kx^n$ equation but with n equal to –1.5, while the constant K is equal to the product of two other constants, one of which is a property of a material's friability, while the other is a representative particle size. The Bond formula, then, is given as

$$[1] \qquad E = 10W_i\left(\frac{1}{\sqrt{x_f}} - \frac{1}{\sqrt{x_i}}\right)$$

in which E is the energy per unit mass to pulverize it from the initial to final state, while x_f and x_i represent the final and initial particle sizes, respectively, expressed in microns (μm). The term W_i is known as the Bond Work Index, which is the energy required to pulverize a given rock-type material from theoretically infinite size to 100 microns (Holdich 2003). Thus, the factor 10 in eq. [1] is actually $\sqrt{100}$ μm, thus providing dimensional consistency. Traditionally, E and W_i are both established in units of kilowatt hours per ton (kWh/t). However, while maintaining the Bond Work Index W_i in units of kWh/t, the energy per unit mass E can be obtained in units of J/kg by multiplying the right hand side of the eq. [1] by 3600.

For our purposes, the Bond based energy of pulverization is employed because it is simple to apply and yields reasonable results for a wide spectrum of particle sizes, ranging from ore bodies and large slabs down to dust particles. Application of eq. [1] to crushing, grinding, blasting, etc. hinges on establishment of a reasonable estimate of a value for the Bond Work Index W_i. Despite an apparent limitation for applications generally having a variety of particle size distributions, it has been shown that reasonable estimates can be computed using W_i for size reductions other than to 100 microns. Eloranta (1997), who has worked in the mining and milling of iron ores for many years, states that "Bond's theory of comminution is still widely used today" and serves as a basis for ascertaining energy usage required to break down materials into finer sized particles. A German company, Doering International Corporation (2011), has published Work Index values W_i for many rock-like materials including iron blast furnace slag and cement clinker. The values given for these two materials are 12–16, and 15 kWh/t, respectively. Although there are no values given for concrete, light weight or normal density, there are several ways to provide an estimate of an appropriate W_i value. One would be to simply use an average of the values noted above, namely a value of 15, since it fits the range of one constituent and matches the value of the other. Another approach would be to link W_i to Moh's scale of hardness (Holdich 2003) of a material that is similar in that property to that of the concrete aggregate used in LWC floors. A third method is to correlate the actual energy found in tests (to be described) to energy E in eq. [1]. In this paper, the Bond Work Index W_i from the third approach will be utilized to compute the amount of energy that can be absorbed by LWC floors in buildings. Indeed, it will be noted that this third estimate is considerably below the other two, resulting in a very conservative energy absorption estimate.

Greening (2006) proposed a model for normal structural concrete that was applied to LWC floors in the twin towers, in which it was assumed that cubic shaped particles formed during a comminution process, requires energy based on the pertinent fracture energy constant G_F derived from either wedge-splitting or point loading tests that induce tensile failures. The G_F models may not be applicable to crush types of pulverization, since implicit in these fracture energy computations is that post-elastic tensile deformations proceed without any load resistance offered by the failed concrete. Such an assumption is questionable, especially when slab edges are restrained from displacing laterally, which occurs at slab-to-wall junctions and when shrinkage steel is used in practice to prevent unsightly floor cracks forming during temperature changes (virtually always the case). In either or both instances there will be a significant degree of lateral restraint to boost penetrating resistance and hence increase the energy absorption capability of LWC floor slabs in buildings.

Bažant et al. (2008) utilized the analytical model developed by Greening (2006) to estimate the amount of energy dissipated by a concrete floor. They assumed that the entire volume of floor slab area was impacted by gravity-driven forces during a global collapse event and pulverized the concrete to fine dust by crushing. The analytical model used relied on the specific fracture energy term, G_F, described earlier, with the value reduced to account for LWC as opposed to normal strength concrete. Indeed, there are applications where utilization of such a factor is pertinent (Bažant and Kazemi 1990), and primarily of interest to those involved in fracture mechanics applications as in preventing failures of dams along rock–concrete interfaces (Kishen and Saouma 2004). The values thus obtained are indeed appropriate to brittle materials subjected to tensile stresses alone. However, when a complex stress state of compressive and confinement stresses exist, such a model may have limited applicability.

A better approach to establishing the energy dissipation potential of light weight concrete floor systems is to actually conduct tests intended to simulate the actual loading during a building collapse event. Unfortunately, one can never accurately predict the way in which structural members and other objects will crush concrete in such scenarios, but at least it can be appreciated that localized crush tests are likely more meaningful in analyzing storey-to-storey impacts. Such a scenario is fraught with a complex of unknown circumstances, not least of which pertains to the way in which the upper floor system impacts its lower counterpart. For example, we might imagine a steel girder or connecting beam impacting the floor below to cause localized crushing in the area of contact. On the other hand, there might be furnishings or interior partitions that could provide a "cushioning effect." Clearly, the possibilities in reality are endless, however, that should not serve as a deterrent for avoiding the problem. However, it does suggest that simplifying assumptions are essential if any progress is to be made into an investigation of this kind. Since an array of floor beams or trusses would be the major structural elements of an upper storey impacting the floor below, a series of patch loads of different area ratios penetrating into floor slabs was conceived. Details of the tests undertaken are described below.

The experimental program

The experiments involved low strength, light weight aggregate that would meet the standards for light weight concrete (LWC). "Truelight" blast furnace aggregate obtained from Lafarge Slag Inc. in Hamilton, Canada, was used in a concrete mix design that was formulated as per recommendations by the National Slag Association (1980). Three concrete cylinder tests were performed to determine the compressive strength of the concrete for the single mix batch used for all specimens. An average value of 19.6 MPa was obtained during the period of testing following a 28 day cure-time period. The density of concrete was measured as 1879 kg/m^3.

Specimen designation

All 10 tests conducted on square light weight concrete slabs were of 50 mm (2") in depth, with surface dimensions ranging from 50 mm (2") to 500 mm (20") squares. Six specimens, labeled with "A" had free edges (unconfined), while the other four, identified as "B", were edge supported (confined) with either 38 mm × 38 mm × 3.2 mm ($1^1/_2 \times 1^1/_2 \times {}^1/_8$") steel angles snug tight around the periphery, or aluminum angles of similar size. Threaded steel rods 6.35 mm ($^1/_4$") in diameter were used to fasten the angles together thus forming a box to restrain the edges. Figure 1 shows the arrangements of such attachments. In the specimen labels the numeral preceding the letter indicates a surface dimension in inches. Figure 1 shows specimens 20A, 20B [500 mm × 500 mm (20" × 20")], 10A, and 10B [250 mm × 250 mm (10" × 10")] in the Riehle testing machine at McMaster's Applied Dynamics Laboratory at the end of their respective central load penetration tests.

Loading application and energy dissipation properties

Once the test specimen was centrally positioned on the lower platen of the machine, a 50 mm (2") thick, 50 mm × 50 mm (2" × 2") rigid steel block was located at the middle of the concrete slab with its 2" (50 mm) edges parallel to those of the slab. This cube shaped steel plate was then used for patch loading all 10 test specimens. Simple quasi-static loading at low strain rate was applied to a specimen well beyond the elastic limit, and was stopped when the upper platen plate displaced about half the thickness, i.e,. a penetration of about 25 mm. For any given specimen, the area under its load–displacement curve represents the energy dissipated during that loading event.

Load–displacement plots are presented in Fig. 2 for all specimens. It may be noted in Fig. 2*a* that specimen 20A suffered a much greater decrease in load resistance rate than did specimen 20B. The reason for this difference is that a rigid patch load is better able to laterally displace surrounding pieces of concrete once a radial crack pattern is established if the edges are free (specimen 20A), compared with a case where edge restraint is present (specimen 20B). For the other slab specimens the difference in post-elastic response is even more pronounced. If, for example, we examine the behavior of loading the 250 mm (10") squares (Fig. 2*b*), specimen 10A responded in much the same way as did specimen 20A, while specimen 10B actually had a post-elastic increase in resistance rather than a decrease that was observed for specimen 20B. Failed specimens 20A, 20B, 10A, and 10B contained 5, 6, 6, and 7 large pieces, respectively. Note from Fig. 2*c*, 2*d*, and 2*e* that the other "A" series specimens, also suffered significant drop-offs in load resistance after reaching their maximum values. Again, the break-up patterns were accompanied by cracking of the specimen into several roughly radial cracks that continued to widen and break into smaller pieces as displacement of the patch load continued. On the other hand, the other two "B" series specimens, 5B and 3B responded much like specimen 10B, with resistance dropping slightly beyond the elastic limit, and then carrying on upwards. In the case of specimen 20B, it was observed that a combination of both radial and shearing through-thickness cracks were formed. The latter displacements occurred directly below the loading plate edges. This result suggests that lateral restraint is needed close to a patch load for post-elastic resistance to increase. Indeed, such was the case for specimens 10B, 5B, and 3B all of which were able to attain double the elastic limit load when testing was terminated.

Fig. 1. Patch loading test specimens 20A, 20B, 10A, and 10B.

Instead of having a specimen 2B with all edges restrained (confined), two free-edged specimens were tested instead, and labeled as 2A1 and 2A2. Providing edge restraint would have been meaningless, since compressive loading of a fully confined specimen simply causes its material to compress in all directions with artificial strengths increasing, perhaps until such time as the edge members themselves fail.

As noted in Fig. 2, the energy drain values for the "A" series specimens are very much lower than their edge restraint counterparts, typically differing by a factor of 10, except for the 500 mm × 500 mm (20" × 20") cases where the factor is closer to 5. This clearly suggests the importance of providing lateral restraint when attempting to increase the energy absorption capacity of floor systems. While tests on slabs having steel mesh present were beyond the scope of the experiments considered herein, it is likely that such steel would have a very beneficial effect on post-elastic resistance during a collapse event. Research at Purdue University (Chiu et al. 2011) has shown that the addition of steel fibres to plain concrete can increase the fracture energy by about 400%. Overall, either that shrinkage steel in the form of a grid arrangement of round bars in concrete slabs or steel fibres in concrete slabs would increase the energy absorption capacity of floor systems.

Sieve analysis for determining particle distributions

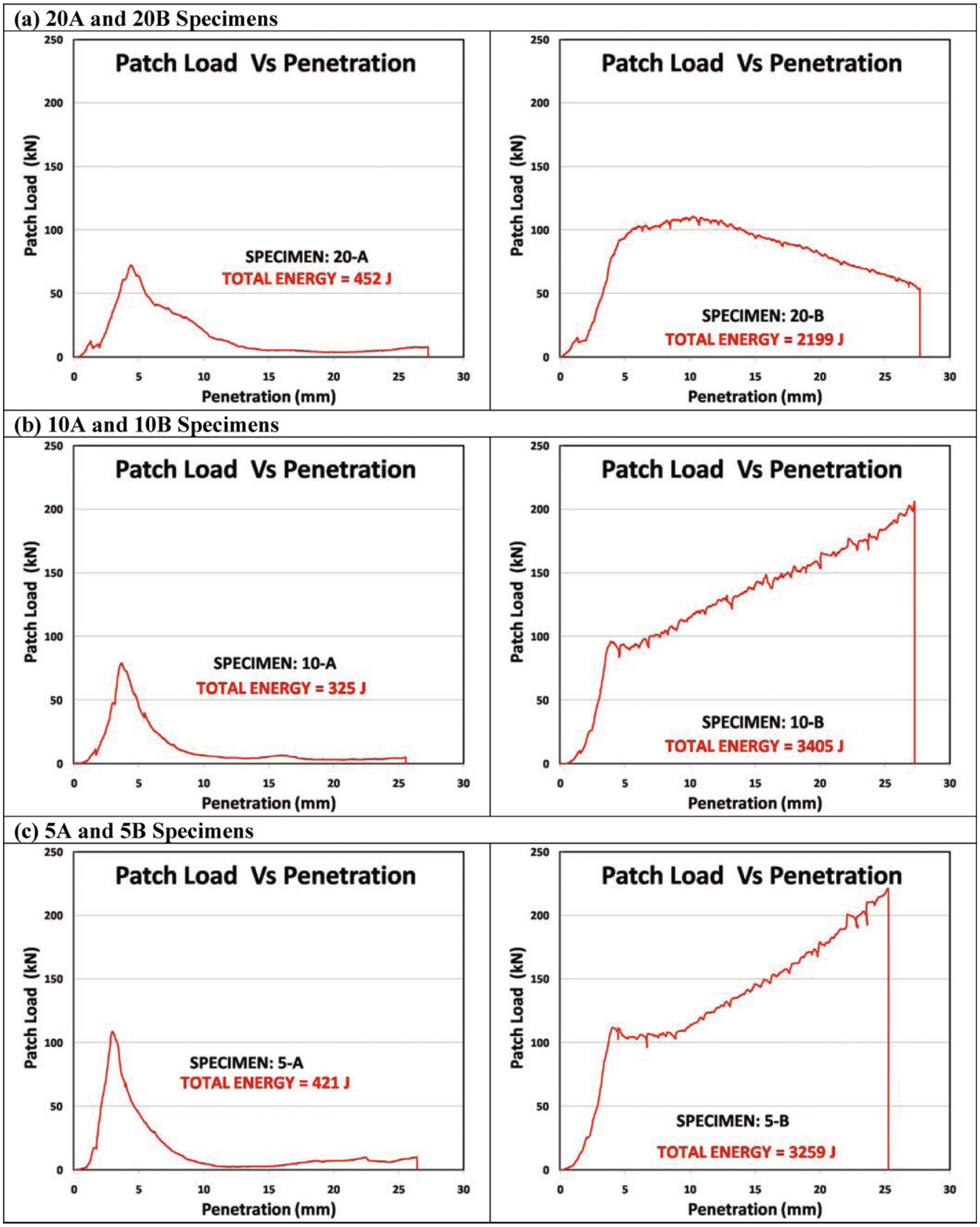
Following a given load penetration test, the broken slab remnants, other than large intact pieces, were subjected to a standard 5 min 8-sieve shakedown to identify the particle sizes associated with the crush experiments. (Fine particles would generally have formed below the rigid patch loading plate). This type of analysis is useful when attempting to relate a form of ablation to energy inputs associated with comminution of materials. In addition, it allows us to draw conclusions about the appropriateness of a "Bond Work Index" value that permits calculations to be made relating pulverization distributions to energy inputs — the latter being important to assessing the energy dissipation potential associated with LWC floor slabs in buildings.

Table 1 gives the breakdown of such an analysis, showing the amounts retained, expressed as a percentage of the original mass of each specimen that was patch load tested. Failed specimens 20A, 20B, 10A, and 10B contained 5, 6, 6, and 7 large pieces, respectively, which were not subjected to sieve shakedown, but were included in Table 1. It is worth noting that when the "A"s are compared to the "B"s for the same size, the latter retained more of the fine particles than did the former, while the reverse is generally the case with the coarse sieve sizes. When examining the energy dissipation results from the slab tests, such an observation makes sense, i.e., more energy input results in a greater degree of pulverization.

Bond work index values for light weight concrete (LWC)

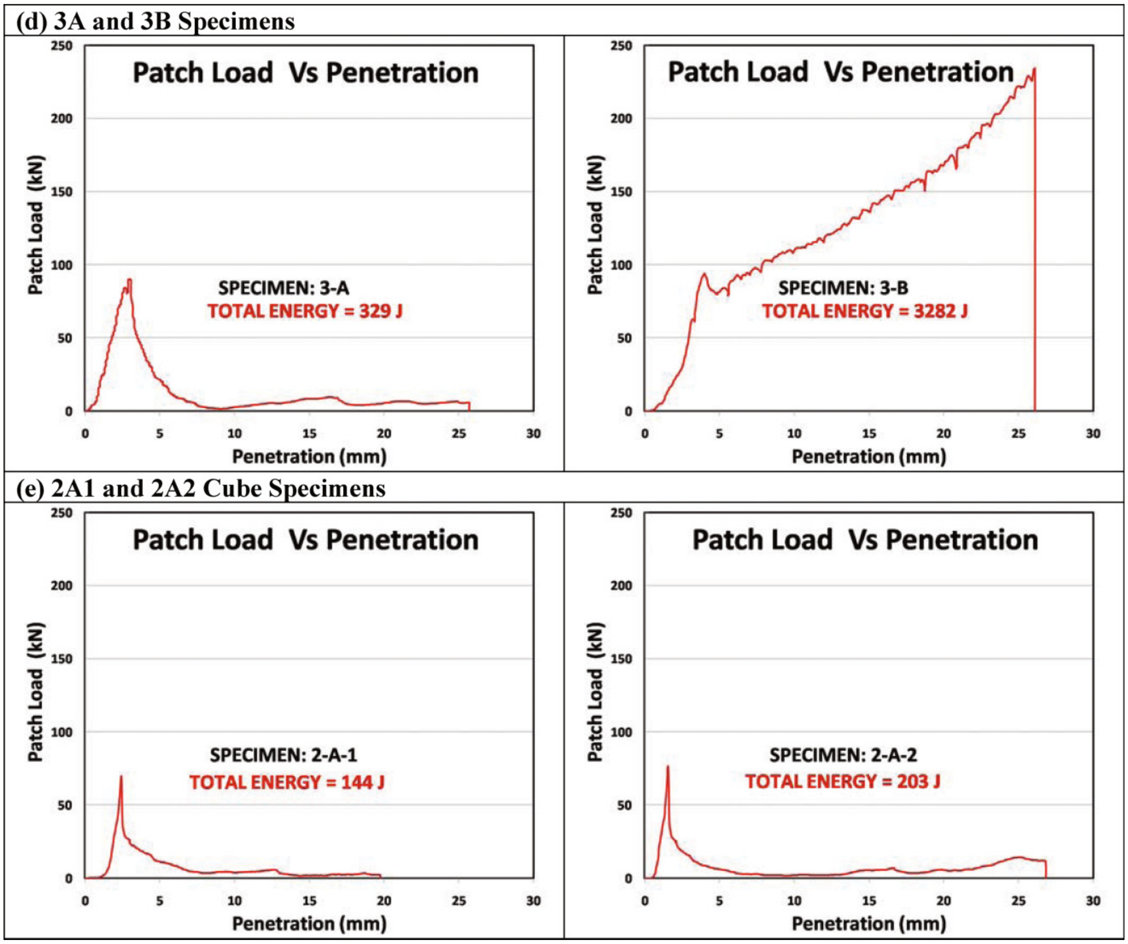
As noted earlier, the Bond formula (eq. [1]) and Bond Work Index offer a promising way to establish the amount of energy needed to crush materials that have brittle properties. This paper uses eq. [1] and the experimental results to obtain Bond Work Index values associated with comminution of uncon-

Fig. 2. Patch load – penetration curves for test specimens.



fined and confined light weight concrete slabs. As an example of how to employ the Bond Work eq. [1] in an energy analysis, we will compute the work done in transforming the mass of specimen 5B retained on the 5 mm sieve. From Table 1, we note that it is 5.45% (0.0545) times 1.54 kg = 0.0839 kg. Since the specimen was originally 127 mm × 127 mm, x_i = 127 000 microns, while x_f = 5 000 microns. Substituting these values into eq. [1] and multiplying by the mass 0.0839 kg gives a value of $34.3W_i$ J. We similarly do the calculations for the other sieve sizes, plus an inclusion for "dust" which constitutes a mass of 0.0156 × 1.54 kg = 0.024 kg. Since the particle sizes in the "dust" category are unknown, a value of 60 μm was chosen. The energy value for the dust is $109.2W_i$ J. Thus the total energy based on all other sieves was determined to be $525.0W_i$ J, noted in Table 2. This value can be compared to the corresponding experimental energy value noted in Fig. 2*c* (also Table 2) of 3259 J. Therefore, the work index value derived from this test is calculated to be W_i = 6.21 kWh/t.

Fig. 2 (*concluded*).



Similar calculations were performed for the other specimens and the corresponding W_i values are given in Table 2.

However, in the paper cited earlier, Eloranta (1997) points out that crushing is far less efficient compared to grinding, and even worse than blasting in particle size reduction technologies. In fact, Eloranta (1997) suggests a factor of 3.4 with which to multiply the energy values from eq. [1] to arrive at a closer estimate to a realistic value for crush energy. By crushing is meant the equivalent of compressing materials between rigid plates without lateral restraint that would offer resistance to material breakdown. A modified work index W_{eq} may be calculated based on Eloranta's (1997) suggested factor of 3.4 by assuming that under the patch load, the energy absorbed by the specimen is governed by the 3.4 factor, whereas the remaining area will be governed by the uncorrected Bond formula given in eq. [1]. Thus, for specimen 5B $W_{eq} = W_i/(3.4 \times 0.16 + 0.84) = 4.49$. Here, 0.16 is the percentage area under the patch load. Table 2 provides an assemblage of Bond Work Index value results. Since we believe that there will be some degree of lateral support, either from a shrinkage steel mesh of one or two layers, a boundary spandrel beam or wall, or even from the ribs of the metal deck onto which the concrete is placed, it is the "B" series with which comparisons must be made. For series "B", on average, the work index value is 4.14, and its value incorporating the correction factor suggested by Eloranta (1997) is 3.48 as noted in Table 2. Thus, we conclude that a Bond Work Index value of 3.48 is reasonable for the light weight concrete floor systems.

Discussion

In circumstances where an extreme loading event can result in a wide range of states of collapse, it seems prudent to suggest a variety of outcomes with respect to the comminution of floor slabs. Consequently, we will consider different hypothetical scenarios to assess the amounts of energy that the LWC slabs would have been able to absorb during a building collapse. As shown in Table 3, Scenario 1 assumes that the entire floor slabs are pulverized into 60 μm dust (Greening 2006). Scenario 2 refers to a comminution case where the floor slab is considered to be pulverized into 50% large 100 mm pieces and 50% 60 μm fine dust. And then, to ascertain the effect of dust fineness on the amount of work energy required, Scenario 3 allows the dust fraction to be divided into equal parts of 60 μm and 30 μm particle fractions. Scenarios 4 and 5 have been arbitrarily added to depict gradations of particle sizes, while Scenario 6 employs approximate distributions obtained from the data for specimen 5B, a photo of which is shown as Fig. 3. This latter case may be somewhat realistic with regard to an actual floor collapse in

Table 1. Specimen details and sieve analysis results (% retained) of failed specimens.

Specimen	Edge condition	Specimen weight (kg)	Large pieces >>20 (mm)	Sieve size 20 (mm)	10 (mm)	5 (mm)	2.5 (mm)	1.25 (mm)	0.630 (mm)	0.315 (mm)	0.160 (mm)	Dust (0.060 mm)
20A	Free	25.3	99.0	0.0	0.26	0.23	0.16	0.09	0.07	0.07	0.05	0.05
10A	Free	6.1	93.4	1.7	1.73	1.20	0.62	0.43	0.26	0.26	0.16	0.25
5A	Free	1.51	0.0	86.9	4.11	2.99	1.92	1.26	0.86	0.86	0.60	0.46
3A	Free	0.60	0.0	54.3	18.05	10.10	5.13	3.48	2.48	2.48	1.82	2.15
2A1, 2A2 (Average)	Free	0.2525	0.0	24.0	26.5	14.8	8.52	5.99	5.68	5.36	4.42	4.73
20B	Confined	25.8	98.8	0.0	0.14	0.24	0.20	0.15	0.11	0.12	0.09	0.14
10B	Confined	6.3	87.8	5.4	2.45	1.26	0.84	0.62	0.45	0.48	0.35	0.50
5B	Confined	1.54	0.0	78.4	5.77	5.45	2.92	2.01	1.36	1.43	1.10	1.56
3B	Confined	0.55	0.0	24.4	24.8	15.5	8.74	6.56	4.55	4.74	3.83	6.92

that it presupposes steel members of whatever description colliding with floor slabs, constituting 16% of the area impacted (50 mm × 50 mm (2” × 2”) patch loading penetrating a 250 mm × 250 mm (5” × 5”) slab). All of this information is presented in Table 3, the purpose being to compute energy drain values and to compare such results with those developed by Greening (2006) and later modified by Bažant et al. (2008).

Table 4 takes the scenarios listed in Table 3 and gives comparative results of energy absorption capacities per kg of LWC from our investigation with results from the models developed by others. The entries in the second column simply employed the Bond eq. [1] directly with a Bond Work Index value of 3.48. The 3rd and 4th columns are the values based on fracture models, one being by Greening (2006) for a material such as normal concrete, the other by Bažant et al. (2008) for LWC.

Since our work index value (W_{eq}) including restraint and crush penetration factors was computed to be only 3.48, our energy dissipation values are about 16% less than the values that the Bond formula for light weight aggregate alone might predict, without including a crush efficiency factor (Eloranta 1997). This result is a bit surprising, but, nonetheless gives surprisingly higher energy values than those obtained by Greening (2006) and Bažant et al. (2008). Our results typically show a fourfold difference with Greening’s model that employed a fracture energy value for G_F = 100 J/kg, while an even greater difference arises when the Bažant et al. (2008) value of G_F = 20 J/kg is employed. Had we chosen to simply use a W_i value based on the Bond formula with the Doering International prescribed value of 15 or one pertaining to perlite (a light volcanic type of rock) for which a value of 11 is suggested, the differences would have been even greater.

Although our own estimate of how effective light weight concrete floor slabs might be in absorbing energy during a building collapse, the complexity of the problem cannot be underestimated. Clearly, more research is needed to link realistic material pulverization models to different scenarios of collapse of buildings that have suffered severe damage due to extreme events. Investigation is also needed on the energy absorption potential of slabs made of normal weight concrete. While engineers and architects can do a great deal to protect lives and property by employing best possible standards and practices, the risks encountered in life cannot be totally eliminated. Nonetheless, it is incumbent on our professions to continue to strive for excellence beyond the norm and to remain vigilant to the unexpected.

Conclusions

Based on the quasi-static penetration tests conducted on concrete slab models that utilized locally produced blast furnace slag aggregate, the applied patch loads were effectively resisted well beyond the yield strain limit of the material. Indeed, for three of the four cases for which edge restraint was employed, the loading path continued to increase above the elastic limit load. It is likely that a layer or two of normal sized steel mesh would similarly provide lateral restraint in a post-elastic state, however, additional tests are needed to confirm such an expectation.

Table 2. Bond work index values for light weight concrete.

Specimen	Experimental energy (J)	Energy based on eq. [1] (J)	Work index value W_i (kWh/t)	Patch/total area ratio	Bond work index value W_{eq} (kWh/t)
20A	452	880.9 W_i	0.51	0.01	0.50
10A	325	522.0 W_i	0.62	0.04	0.57
5A	421	370.2 W_i	1.14	0.16	0.82
3A	329	260.5 W_i	1.26	0.44	0.61
2A1, 2A2	174	184.4 W_i	0.94	1.0	0.28
A - Series average			0.90		0.56
20B	2199	1177.4 W_i	1.87	0.01	1.82
10B	3405	763.6 W_i	4.46	0.04	4.07
5B	3259	525.0 W_i	6.21	0.16	4.49
3B	3282	451.9 W_i	7.26	0.44	3.53
B - Series average			4.14		3.48

Table 3. Hypothetical scenarios: floor slab to particle size distributions.

Scenario	Assumed floor size	Particle size distribution (% retained)							
		100 mm	20 mm	5 mm	1.25 mm	630 μm	160 μm	60 μm	30 μm
1	20 m × 20 m	0	0	0	0	0	0	100	0
2	20 m × 20 m	50	0	0	0	0	0	50	0
3	20 m × 20 m	50	0	0	0	0	0	25	25
4	20 m × 20 m	50	7.1	7.1	7.1	7.1	7.1	7.1	7.1
5	20 m × 20 m	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
6	20 m × 20 m	0	78	11.3	5	1.5	2.6	0.8	0.8

Fig. 3. Specimen 5B following patch test.

Table 4. Hypothetical scenarios: energy comparisons.

Scenario	Energy absorption based on experimental bond work index W_{eq} = 3.48 (kWh/t)* (J/kg)	Energy by Greening (2006)† (J/kg)	Energy by Bažant et al. (2008)‡ (J/kg)
1	16 146	3 333	667
2	8 073	1 667	334
3	9 932	2 501	500
4	4 263	842	168
5	7 138	1 472	294
6	1 611	138	28

*Work index, including a 3.4 factor to account for inefficiency by crush under loading block.

†$E = G_F\,(4000/d)$, where G_F = 100 J/kg and d is the cube-shaped particle size width expressed in microns.

‡Assumed light weight concrete with G_F = 20 J/m².

It is evident, both from the experiments undertaken and on research drawn from the mining and milling industries, that pulverizing light weight concrete by crushing — thus crudely simulating a collapsing upper storey truss or floor beam member — will dissipate a considerable amount of energy. Despite the limitations inherent in the energy dissipation models proposed, we are of the opinion that LWC floor slabs, having the standard content of shrinkage steel as specified in practice, do indeed offer a significant degree of resistance to motion caused by gravity driven forces.

Acknowlegement

The authors wish to express sincere appreciation to John Westoby of Lafarge Slag Inc. for providing the Truelight aggregate that was used in the light weight concrete slab tests.

References

Bažant, Z.P., and Kazemi, M.T. 1990. Determination of fracture energy, process zone length and brittleness number from size effect with application to rock and concrete. International Journal of Fracture, **44**: 111–131. doi:10.1007/BF00047063.

Bažant, Z.P., Le, J.-P., Greening, F.R., and Benson, D.B. 2008. What did and did not cause collapse of the WTC twin towers in New York. Journal of Engineering Mechanics, **134**(10): 892–906. doi: 10.1061/(ASCE)0733-9399(2008)134:10(892).

Bond, F.C. 1952. The third theory of comminution. Mining Engineering Journal, **193**: 484–494.

Chiu, Y.-C., Panchmatia, P., and Sivaran, A. 2011. Analysis of Fracture Energy: Comparative Study of PCC and FRC. Purdue University report. (https://engineering.purdue.edu/~zavattie/Fracture/reports/Team6-report.pdf).

Doering International Corporation. 2011. Grinding Media Size Formula–Work Grinding Work Index for Different Materials According to Bond. Sinn, Germany.

Eloranta, J. 1997. The Efficiency of Blasting Versus Crushing and Grinding. Proceedings of the 23rd Conference of Explosives and Blasting Technique. Las Vegas, Nevada. February. pp. 1–7.

Fuerstenau, D.W., and Somasundaran, X.X. 1965. Comminution Kinetics. 6th International Mineral Processing Congress held at Cannes, 1963. Proceedings of Pergamon Press, London. pp. 25–34.

Greening, F.R. 2006. Energy Transfer in the WTC Collapse. WTC Report. February. 5 p.

Holdich, R. 2003. Fundamentals of Particle Technology. Loughborough University, United Kingdom. pp. 113–116.

Kick, F. 1885. The Law of Resistance and its Use. Leipzig, Germany. (in German).

Kishen, J.M.C., and Saouma, V.E. 2004. Fracture of rock-concrete interfaces: laboratory tests and applications. ACI Structural Journal, **101**(3): 1–7.

National Slag Association. 1980. Pelletized Lightweight Slag Aggregate, prepared by J.J. Emery for Concrete International. pp. 1–6.

Schuhmann R., Jr. 1960. Energy input and size distribution in comminution. Trans. AIME, 217: 22–25.

Von Rittinger, P. 1867. Manual for Aggregate Processing. Germany. (in German).