Seventh International Conference on Construction in the 21st Century (CITC-VII)
"Challenges in Innovation, Integration and Collaboration in Construction & Engineering"
December 19-21, 2013, Bangkok, Thailand

Energy Dissipation Potential of Concrete Floors Containing Temperature Shrinkage Control Reinforcements

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Abstract
This paper experimentally investigates the energy dissipation potential of two types of concrete floors, namely, normal concrete and light weight concrete containing temperature shrinkage reinforcements. The test program considered the following temperature shrinkage reinforcements; (a) traditional welded-wire steel mesh, (b) steel fiber and (c) poly composite fiber. To estimate the extent to which crushing of floor slab materials would help absorb energy, a series of concrete penetration tests employing patch loading was undertaken on scaled down model slabs. Each combination considered square concrete slabs of 50 mm in depth, and with square plan dimensions ranging from 50 mm to 500 mm, resulting in a total of 30 test specimens. The first part of the paper discusses the specimens, the test setup, and the test procedure. The second part of the paper presents the experimental results and establishes the energy dissipation of different concrete - temperature shrinkage reinforcement combinations. Sieve analysis results of the crushed specimens were used to derive a "work index" value that relates pulverization distributions to energy inputs, which can be used to assess the energy dissipation potential associated with floor slabs in buildings undergoing progressive collapse. The results indicate that floors with temperature shrinkage reinforcements could play an important role in helping arrest global progressive collapse mechanisms.

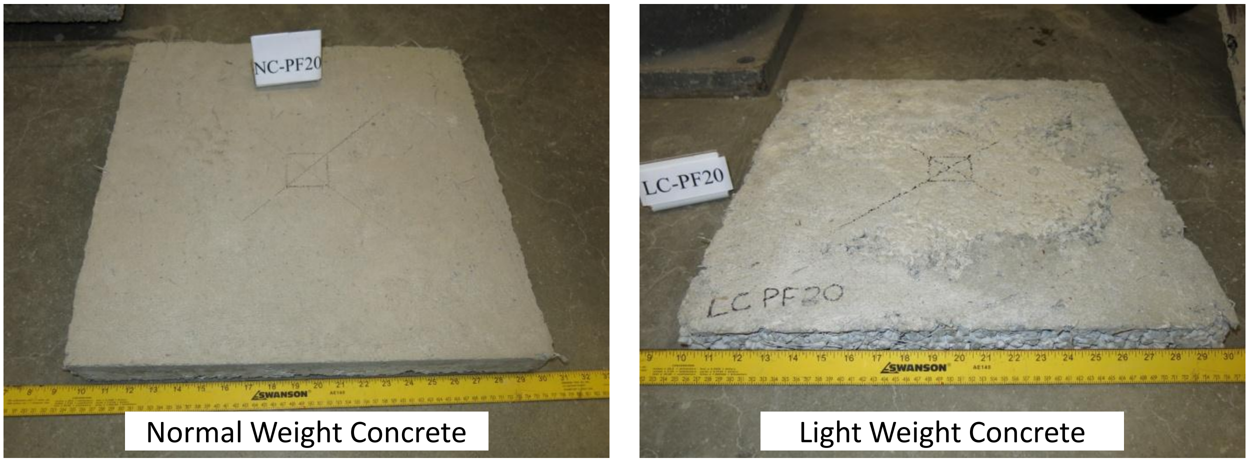
Keywords
Concrete floors**,** Light weight concrete, temperature and shrinkage reinforcements, Energy dissipation, Penetration tests, Sieve analysis

1. Introduction

The energy absorption capability of concrete floors to mitigate building progressive collapse during some extreme loading event is of interest to structural designers. If the concrete floor can absorb the energy by localized mechanism instead of structural collapse, then the damage will be restricted to that floor. One potential scenario is that one flange of a floor beam strikes onto the slab immediately below, penetrating its surface and causing localized pulverization. Depending on the energy absorption capability of that impacted slab, the collision will stop right at that floor or continue all the way down to the foundation. This paper explores the degree of resistance and energy absorption provided by the concrete floor slabs. The primary objective of this research project is to compare the energy absorption capacities of slabs consisting of two kinds of concrete namely, normal weight and light weight concrete, and three types of shrinkage and temperature reinforcements, namely steel mesh, steel fiber and polypropylene fiber. Concrete was mixed in-site and patch load test was conducted on the slab specimens. The effects of concrete type, type of temperature and shrinkage control reinforcement, and the test specimen dimension on the energy absorption capacity are investigated. Bond Work Index which relates the particle size distribution of the specimen remnants to the dissipated energy is computed.

2. The Test Specimens

Korol and Sivakumaran (2012) used patch load tests on scaled down model slabs to explore the energy absorption potential of unreinforced light weight concrete floors. Their tests considered square specimen sizes ranging between 50 mm and 500 mm and having unrestrained edges and restrained edges. All specimens were of thickness 50 mm. The energy absorbed by each specimen was established based on load-penetration relationship, and the results showed that the light weight concrete slabs with restrained edges can absorb more energy compared to the same specimens with free edges. The investigation presented in this paper can be viewed as an extension of that previous study. In order to provide a continuity and facilitate comparison, the current investigation considered specimens having the same dimensions as those of the previous study by Korol and Sivakumaran (2012). All specimens were of same thickness of 50 mm, however, five different square slabs of 50 mm x 50 mm, 75 mm x 75 mm, 125 mm x 125 mm, 250 mm x 250 mm and 500 mm x 500 mm sizes were considered. As usual, the concrete was mix-designed using ordinary Portland cement, fine aggregates (sand), chemical admixture, water, however, as indicated earlier, one set of specimens was prepared with normal weight coarse aggregate with a nominal maximum size of 10 mm, whereas, the other set of specimens was prepared with light weight aggregate known as "Truelight", obtained courtesy of Lafarge Slag Inc. in Hamilton, Canada. Based on the sieve analysis, the nominal maximum size of light weight aggregate was determined to be around 10 mm. The bulk density and the specific gravity of the normal weight aggregate and the light weight aggregate were 1483 kg/m^3 and 2.65, and 761 kg/m^3 and 1.65, respectively. Figure 1 shows the photographic images of the specimens made of normal weight concrete and the light weight concrete.



This study considered steel mesh, steel fiber and polypropylene fiber as shrinkage and temperature reinforcements. The Figure 2 shows the photographic images of these reinforcements. The steel mesh wires had a diameter of 3.1 mm and were oriented orthogonally and were welded to each other. Thus, the steel mesh used in this study had aperture sizes of 50 mm x 50 mm. One layer of that steel wire mesh was placed in the middle height of the slab which gave a steel cross-sectional area to gross concrete area ratio of 0.003. According to ACI 318 (ACI, 2008), the minimum required ratio of shrinkage and temperature reinforcement area to gross concrete area is 0.002. The steel fibers used this study were Wirand® Fiber FF1 obtained from Maccaferri from the U.S.A. They have a diameter (D) of 1.00 mm, and a length (L) of 50 mm and thus, an aspect ratio (L/D) of 50. The ends of Wirand® Fiber FF1 are mechanically deformed in order to provide better anchorage in concrete. According to the technical data sheet issued by the company, the tensile strength of the wire is larger than 1100 MPa and the ultimate strain is smaller than 4% (MACCAFERRI, 2012). Wirand® Fiber FF1 meets the requirements of ASTM A820 (ASTM, 2006). The dosage of 45 kg fibers per cubic meter concrete was recommended by the manufacturer, which was used in the production of the test specimens. The polypropylene fibers MasterFiber™ MAC Matrix was purchased from BASF chemical company in Hamilton, Canada. According to the product data from the company, MasterFiber MAC Matrix is a macrosynthetic fiber manufactured from a proprietary blend of polypropylene resins. It is a stick-like embossed fiber having an available length of 48 mm. The tensile strength of it is 585 MPa (BASF Corporation, 2012). According to the manufacturer, the MasterFiber MAC Matrix product meets the requirements of ASTM C 1116/C 1116M (ASTM, 2010) and is a true replacement for welded wire reinforcement (steel mesh) and steel fiber depending on the application. The

Figure 1: Test Specimens made of Normal Weight Concrete and Light Weight Concrete

manufacturer recommended a dosage of 9 kg/m^3 MasterFiber MAC Matrix to be equivalent to 45 kg/m^3 steel fibers. This dosage was used in the production of polypropylene fiber containing test specimens. Sufficient concrete for three types of concrete-reinforcements combinations was initially mixed, and was

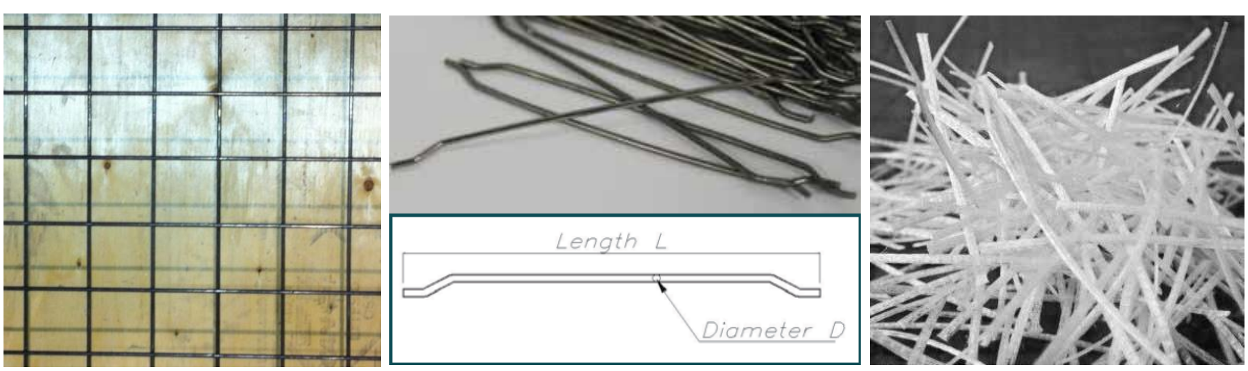


Figure 2: Shrinkage and Temperature Reinforcements - Steel Mesh, Steel Fiber, and Polypropylene Fiber

divided into three parts. One part of the concrete was used to make the specimens containing steel mesh. The remaining concrete was divided into two equal parts and transferred to two different concrete mixers. The respective fibers were dispensed slowly into the concrete mixer containing the corresponding part of concrete. The chemical admixture GLENIUM 7500, a high-range water-reducing admixture from BASF, was used to avoid fiber balling and to distribute the fibers uniformly in the mixture.

Compressive strength test cylinders were also made as part of the test program. Unfortunately, at times, the available concrete for these test cylinders was inadequate. Thus, either two or three such cylinders were made for the six types of concrete reinforcement combinations indicated below. Tests for compressive strength followed ASTM C39/C39M, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM, 2005), and the cylinders were tested during the same time period as the tests of the slab specimens. Based on the cylinder tests, the following compressive average strengths were recorded for the associated concrete reinforcement combinations shown; Plain normal weight concrete (NC)- 40.9 MPa, Normal weight concrete with steel fiber (NC-SF)- 47.4 MPa, Normal weight concrete with polypropylene fiber (NC-PF)- 47.3 MPa, Plain light weight concrete (LC)- (19.8 MPa, however, this value is not usable due to defective test cylinders), Lightweight concrete with steel fiber (LC-SF)- 37.7 MPa, and Lightweight concrete with polypropylene fiber (LC-PF)- (14.1 MPa, however, this values is not usable due to defective test cylinders). Obviously, the strength of light weight concrete is lower than the normal weight concrete. Note however, different mix designs were used for these two concretes, which can lead to different strengths. In general, the fibers increase the effective compressive strength of concrete.

The test program considered a total of thirty slab specimens, consisting of 15 normal weight concrete - reinforcement combinations, and another 15 light weight concrete - reinforcement combinations. Each of these combinations had five different specimen sizes. For convenience of identification, each specimen was assigned a name such as NC-SM20. The first two letters indicate the type of the concrete used, such as "NC" means normal weight concrete and "LC" means light weight concrete. The second two letters represent the type of shrinkage and temperature reinforcement used, such as, "SM" for steel mesh, "SF" designates steel fiber and "PF" indicates polypropylene fiber. The number in the end is the surface dimension of the specimen given in inches. Therefore, for instance, "NC-SM20" stands for a specimen consisting of normal weight concrete reinforced with steel mesh and having a square surface dimension of 500 mm (20") by 500 mm (20").

3. The Test Setup

The patch tests described herein were conducted on a 600 kN capacity Tinius Olsen hydraulic universal testing machine, which has a fixed lower platen and a displacement controlled movable upper loading platen. The specimens were subjected to a patch test, for which a 50 mm x 50 mm square shaped patch load was created by a 50 mm (2") thick, 50 mm x 50 mm (2" x 2") rigid cubic steel loading block centrally welded underneath the upper platen. The Figure 3 shows the overview of the test setup including a specimen ready for the test. The test specimen was fully supported on the lower platen of the test machine, albeit on steel blocks. In order to ensure that the test specimen was centrally loaded by the patch load, the intended loading area was drawn on the top surface of the test specimen. Some test specimens didn't have a smooth top surface finish, however, the target patch loading area was ground smooth so that the steel block may apply a uniform patch load. A calibrated Linear Variable Differential Transformer (LVDT) was centrally installed on the top platen, to measure the penetration of the steel block into the concrete specimen. The upper platen was lowered to bring the loading block to come in contact with the test specimen, and if needed, the test specimen was adjusted and re-centered. Once the specimen is centered and the patch load steel block is determined to be parallel to the specimen edges, a transparent plastic protective frame was placed around the specimen in order to confine the concrete fragments produced during failure. The patch load was applied in a displacement control mode, with an initial loading rate of 0.5 mm/min, however, the loading rate was increased during the latter stages of the test. The LVDT readings and the load cell readings from the machine were recorded and stored at every second. The loading was terminated when the specimens had experienced a penetration of about 25 mm, which is the half thickness of both the steel block and the test specimens. After each patch load test, each fragment of the each test specimen was carefully collected and stored in a container for subsequent weighing and sieve analysis.

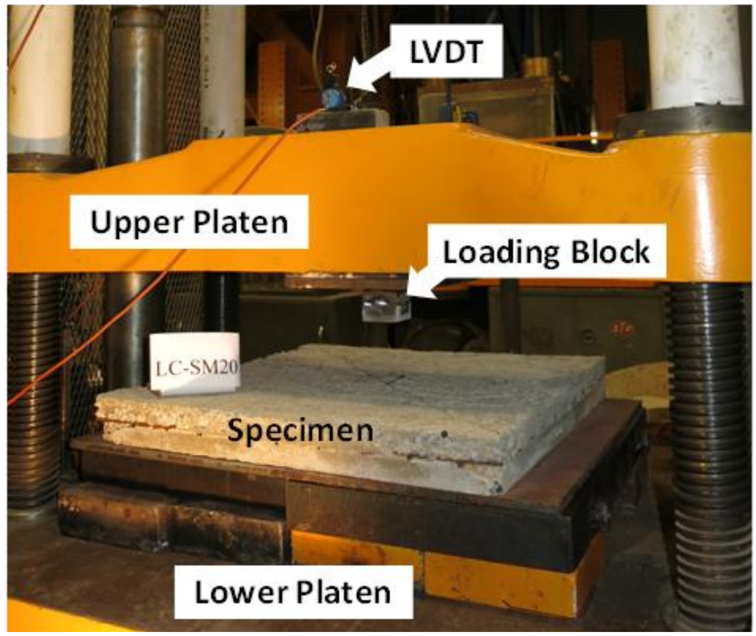


Figure 3: The Test Setup and a Test Specimen

4. The Test Results

Figure 4 shows photographic images of some of the test specimens after failure, highlighting the failure modes. At a penetration of 25 mm, some test specimens, smaller specimens in particular, were completely destroyed into small fragments. Larger pieces of fragments can be observed in 75 mm specimens. In these specimens, the steel mesh and steel fiber reinforcements appeared to have been pulled out of the concrete intact, showing a bonding failure. However, the polypropylene fibers in 75 mm specimens appear to have experienced a combination of bond failure in some fibers and fiber damage, including breakage, in others. Larger test specimens (i.e. 125 mm, 250 mm and 500 mm) exhibited different failure modes. Perhaps because of the sufficient bonding provided by the shrinkage and temperature reinforcements, the patch load does not easily pulverize these large specimens. As may be evident from Figure 4, the concrete right underneath the patch load may be pulverized in larger specimens, however, the remaining parts break into large pieces. The cracks that are formed in locations outside the patch load, at times, do not even cause a complete fracture when the load had penetrated the specimen by 25 mm. Essentially, the reinforcements held these cracked large pieces together.

Figure 4: Specimens After Tests - Representative Failure Modes

Figure 5 shows the load - penetration relationships obtained from these tests. The vertical axis shows the measured load in kN, whereas the horizontal axis shows the measured penetrations. Note that, the graphs focus on a maximum penetration of 25 mm, though the experimental penetrations associated with some specimens may be slightly larger than 25 mm and the additional data points beyond 25 mm had been ignored. In general, all thirty test specimens exhibited similar behavior, in that the behavior consists of several distinct regions like initial settlement reflected by lower stiffness followed by stiffer region where the specimens resist increasing loads at low penetrations. End of the stiff region can be associated with reaching of the peak loads, which is followed by a reduction in load resistance accompanied by significant penetrations. Often peak load is associated with the first crack. Table 1 shows the experimental peak loads registered by different test specimens. It may be evident from this table, that in general, larger specimens sustained larger loads. Also, it is observed that the normal weight concrete sustains larger loads than its counterpart light weight concrete. Concrete containing steel mesh type reinforcements sustained higher loads compared to concrete specimens containing steel fiber type shrinkage and temperature reinforcements. Although not definitive, concrete containing polypropylene fibers resisted lower loads compared to concrete with other two types of shrinkage and temperature reinforcements.

Table 1: Experimental Peak Loads for Normal Weight Concrete Specimens and Light Weight Concrete Specimens having Shrinkage and Temperature Reinforcements

Specimen Size	Concrete - Reinforcement Combinations and the Corresponding Peak Loads					
	NC-SM	**NC-SF**	**NC-PF**	**LC-SM**	**LC-SF**	**LC-PF**
50 mm (2”)	108 kN	90 kN	54 kN	51 kN	21 kN	25 kN
75 mm (3”)	207 kN	171 kN	140 kN	93 kN	76 kN	77 kN
125 mm (5”)	307 kN	269 kN	289 kN	148 kN	131 kN	115 kN
250 mm (10”)	385 kN	319 kN	181 kN	209 kN	120 kN	100 kN
500 mm (20”)	471 kN	430 kN	301 kN	358 kN	169 kN	207 kN

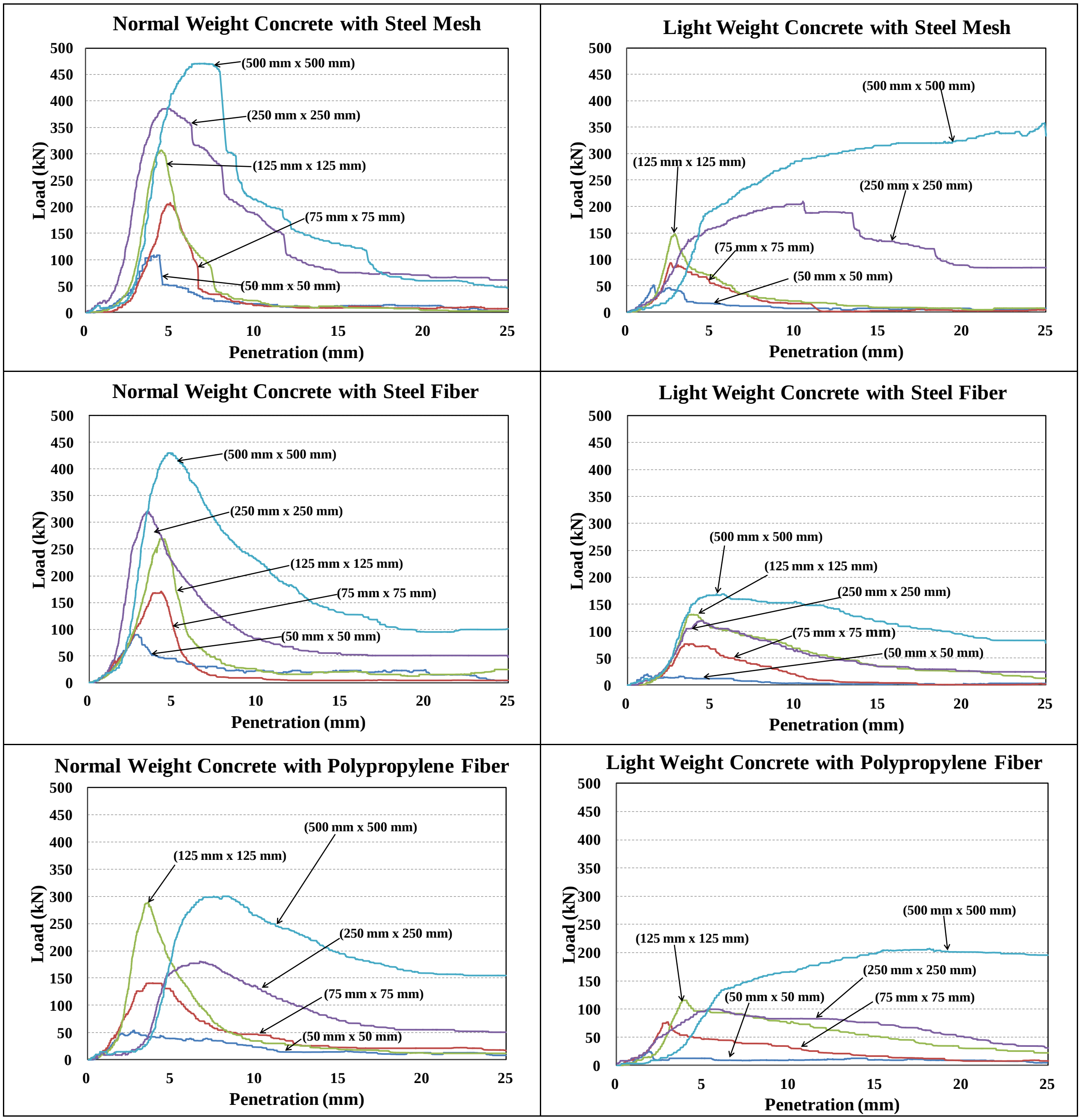


Figure 5: Load Penetration Relations for Normal Weight Concrete and Light Weight Concrete having Shrinkage and Temperature Reinforcements

The energy imparted on a specimen during 25 mm penetration can be established as the area under the load penetration diagram. This is the energy absorbed by the specimen. The energy absorption potential of normal weight concrete floors and light weight concrete floors having shrinkage and temperature reinforcements have been tabulated in Table 2. It is apparent that, in general, the normal weight specimens absorbed higher energy, ranging between 0.7 times and 4.5 times, compared to the light weight counterparts for different type of shrinkage and temperature reinforcements. Absorbed energy increased with increasing size of the specimens. For example, the 500 mm x 500 mm normal weight concrete specimen containing steel mesh absorbed eight times more energy compared to the 50 mm x 50 mm of the same material combination.

Table 2: Energy Absorption Potential of Normal Weight Concrete Floors and Light Weight Concrete Floors having Shrinkage and Temperature Reinforcements

Specimen Size	Concrete - Reinforcement Combinations and Corresponding Energy Values					
	NC-SM	**NC-SF**	**NC-PF**	**LC-SM**	**LC-SF**	**LC-PF**
50 mm (2”)	526 J	636 J	540 J	291 J	140 J	243 J
75 mm (3”)	762 J	600 J	1128 J	462 J	454 J	619 J
125 mm (5”)	1080 J	1136 J	1364 J	654 J	1229 J	1335 J
250 mm (10”)	3597 J	2380 J	2112 J	3187 J	1244 J	1614 J
500 mm (20”)	4210 J	4411 J	4463 J	6416 J	2828 J	3757 J

Energy density can be established as energy per unit volume of specimen. Energy density decreases with increasing size of specimen. For example, the energy density of 50 mm x 50 mm normal weight concrete containing polypropylene fibers was 4.32, whereas those of 125 mm x 125 mm and 500 mm x 500 mm were 1.75 and 0.36, respectively. This is because all of the specimens were subjected to the same patch load of 50 mm x 50 mm at the middle of the specimen, and the energy absorbed by the materials away from the patch load location, may be less than that absorbed by the material right under the patch load. From an energy point of view, normal weight concrete with steel fiber absorbed between 66% and 121% (average 95%) energy compared to same concrete containing steel mesh. Corresponding comparison for light weight concrete was between 44% and 188% (average 83%). The normal weight concrete with polypropylene fibers absorbed between 59% and 148% (average 108%) energy compared to same concrete containing steel mesh. Similar results for light weight concrete was between 51% and 204% (average 106%). Based on energy values, unfortunately there is quite bit of scatter in the results and thus, we are unable to choose one type of shrinkage and temperature reinforcement over the other. However, these energy values are in between the energy values for light weight concrete, unconfined and fully confined, test specimens reported by Korol and Sivakumaran (2012).

In view of the page limitations, here, we briefly discuss the further analysis of test results. After each patch load test, the small fragments and large pieces of the failed specimen were carefully collected and the weight of the large pieces (size > 50 mm) were recorded. During the 25 mm penetration tests, all of the 50 mm specimens were reduced to particles less than 50 mm, whereas, about 70%, 20%, 6%, and 2% of the 75 mm, 125 mm, 250 mm, and 500 mm specimens, respectively, were reduced to smaller particles(< 50mm). Essentially, the larger specimens containing shrinkage and temperature reinforcements broke into larger pieces with minimal pulverization, primarily occurring under the patch load. The remnants that were less than 50 mm in size were subjected to a standard five minutes 8-sieve analysis in order to establish the particle size distribution and the associated weights. Based on particle size distribution, which includes the large pieces, and the energy values shown in Table 2, one may establish a bond work index using the bond formula (Bond, 1952). The Bond Work Index is the energy required to pulverize a given rock-type material from theoretically infinite size to 100 microns (Holdich, 2003). Although the detailed calculations are not given herein, and are available in the thesis by Fan (2013), the average bond work index values for the concrete reinforcement combinations are; Normal weight concrete with steel mesh(NC-SM)- 3.4 kWh/t, Normal weight concrete with steel fiber (NC-SF)- 3.4 kWh/t, Normal weight concrete with polypropylene fiber (NC-PF)- 3.7 kWh/t, Light weight concrete (LC-SM)- 13.4 kWh/t, Light weight concrete with steel fiber (LC-SF)- 2.4 kWh/t, and Lightweight concrete with polypropylene fiber (LC-PF)- 11.0 kWh/t.

5. Concluding Remarks

The energy absorption capability of concrete floors to mitigate building progressive collapse during some extreme loading event is of interest to structural designers. The primary objective of this research project is to compare the energy absorption capacities of slabs consisting of two kinds of concrete namely, normal weight and light weight concrete, and three types of shrinkage and temperature reinforcements, namely steel mesh, steel fiber and polypropylene fiber. The test program considered a total of thirty slab specimens, consisting of 15 normal weight concrete - reinforcement combinations, and another 15 light weight concrete - reinforcement combinations. Each of these combinations had five different specimen sizes. The specimens were subjected to a 50 mm x 50 mm patch load. The normal weight concrete sustains larger loads than its counterpart light weight concrete. Overall, it must be acknowledged that the behavior of light weight concrete is erratic because it was difficult to make a well compacted light weight concrete specimen with fibers and because the surface finish was not smooth and thus might have been subjected to load concentrations. The energy absorbed by the specimen during a 25 mm penetration was established as the area under the load penetration diagram. In general, the normal weight specimens absorbed higher energy. The three shrinkage and temperature reinforcements under consideration improved the energy absorbing potential of the concrete. The average bond work index values established for the concrete reinforcement combinations may be used to establish the energy absorbing potentials of building floors.

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