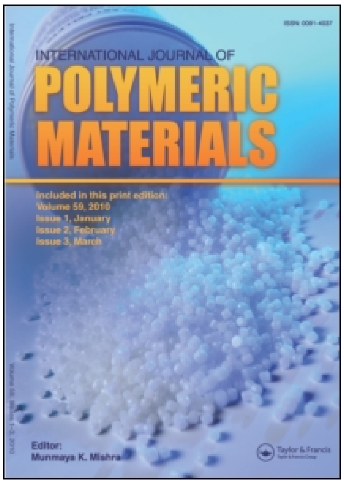


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# Enhancing Concrete Strength and Thermal Insulation Using Thermoset Plastic Waste

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# Enhancing Concrete Strength and Thermal Insulation Using Thermoset Plastic Waste

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*Structural concrete is the most frequently used construction material in the world because of its known advantageous characteristics. However, concrete has some limitations, such as its low tensile strength, low strength-to-weight ratio and moderate thermal insulation. Improving these characteristics was the aim of a laboratory-based investigation into the behavior of concrete made in the presence of ground melamine-formaldehyde (MF) thermosetting plastic waste as a sand replacement. The MF is a cross-linked thermoset polymer that cannot be recycled or reprocessed, presenting a serious solid waste disposal problem. The laboratory-based program included tests of tensile and compressive strengths, unit weight and thermal insulation characteristics. The tests were carried out on concrete and mortar with various water-to-cement (w/c) ratios, and sand was replaced by MF at different percentages that ranged from 0% to 60%. The results indicated that replacing sand with MF resulted in a lighter-weight concrete with improved characteristics. In general the strengths were increased as the percentage of MF was increased to reach maximum values at approximately 30% MF. In comparison with control specimens without MF, the strength/weight ratio of concrete was increased by up to 47% and the tensile strength of mortar was increased up to 16%. With regards to thermal insulation, a drop in temperature up to 30% was recorded in specimens with 60% MF. In conclusion, this investigation showed that the addition and reuse of MF in concrete mixes significantly improved the mechanical and thermal characteristics of concrete. This would be an effective approach when added to other protection methods of solid waste, as it addresses the specific waste of MF.*

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**Keywords:** concrete, mortar, recycling, solid waste, strength, tests, thermal insulation, thermoset plastics



## INTRODUCTION

Modernization and progress contributed significantly to the degree of pollution that societies all over the world are facing. This has raised a great deal of concern among the public about the various dangers of pollution observed in air, water and soil. With the global population increasing and the rising demands for various essentials and luxuries, there has been a rise in the amount of waste being generated by households and industry. This waste is ultimately disposed of at waste collection centers, where it is collected to be transferred into landfills and dumps. However, due to limited resources or inadequate infrastructure, not all of this waste is collected and transported to the final dumping sites, which may have a serious impact on human health and the surrounding environment. Waste treatment and disposal sites can also create health hazards for the neighborhood. Improperly operated incineration plants cause air pollution. Improperly managed landfills attract all types of insects and rodents that may spread disease.

In particular, solid waste that is not properly managed may cause serious health hazards and spread infectious diseases. Unattended solid waste attracts flies, rats and other creatures that in turn spread disease and also increase the risk of injury. Uncontrolled solid waste, especially plastics, can also obstruct storm water runoff, resulting in the forming of stagnant water bodies that become the breeding ground of disease. Thus the solid waste problem must be addressed properly and preventive measures must be adopted to manage and control this problem.

Throughout the world and for a long period of time, different methods have been used to manage solid waste. Two of the oldest methods are landfilling and burning. Burning became popular in many areas of the world because it reduces the volume of solid waste up to 90%, kills bacteria and germs and reduces the amount of waste to be landfilled. However, burning may pollute the air. A clearer picture is still required to agree upon effective solutions to environmental challenges related to solid waste disposal. An integrated approach to resource management is believed to be the most effective way to achieve safe and economical results. An integrated approach selectively utilizes source reduction, reuse where appropriate, resource recovery including materials recovery through recycling, energy recovery and, finally, retention in landfill. Increasing the rate of recovery and reuse of waste material will assist in the protection of human health and the environment from the hazards posed by waste, and will help in the conservation of energy and natural resources.

Solid waste may be defined to include durable goods, containers and packaging, food wastes, yard wastes, and miscellaneous inorganic wastes from residential, commercial, institutional and industrial sources [1]. In particular, plastic is a material that somehow succeeds at nature's expense, indifferent and perhaps even hostile to the concept of conservation. It should be mentioned that not all plastic materials are recyclable, and because plastic materials do not easily degrade they are harmful to the environment and greatly complicate waste management efforts.

It is estimated that the solid waste produced in the Palestinian area is 2500 tons per day, of which plastics are estimated at 8%–12%.

The investigation of MF use in Palestine revealed that its use is mainly in molding dishware, with about 10% loss during manufacture. This may be attributed to the use of old equipment, lack of quality controls and quality assurance, lack of well-trained workers, poor working conditions and the use of raw materials that exhibit inferior quality. The waste produced during manufacturing and end use contributes to the total solid waste problem in Palestine.

The volume of plastic solid waste is extremely large worldwide and increases with time. For example, in the USA, more than 209 million tons of solid waste were generated in 1994 [2]. The plastics accounted for 19.8 million tons (about 10%). The Environmental Protection Agency in the USA estimates that solid waste increases at a rate of 4.5% per year [3] where plastics, rubbers, and textiles account for 20% by weight and 41% by volume of the total solid waste. However, only 6% of plastics, rubbers and textiles were recovered for recycling [4].

Considering the large volume of solid waste, the reuse of recovered materials would become economically feasible especially if appropriate practical applications were introduced. This clearly indicates the need for further efforts to reuse plastics, i.e., the use of recovered materials by a manufacturer to produce a new product with modified properties. To support the reuse process, it is important to assure that uses for the recovered materials are available. Reuse programs will benefit more local industries that want to reuse recovered materials and more consumers who asked for products made with recovered materials. This will be possible if the new products have better characteristics and are cost-effective. In this regard the research work described in this article focused on the reuse of polymer waste, e.g., thermoset plastics that can not be recycled in producing concrete with enhanced characteristics. This approach will not only help in protecting the environment and public health but also will help in solving some technical problems in the construction industry field.

## RESEARCH SIGNIFICANCE

Plastics are a major source of solid waste and the thermoset melamine-formaldehyde (MF) is a very common source of this waste. Considering the economic and environmental costs of landfilling or burning, it is necessary to adopt no-waste technology and to encourage the implementation of reuse and recycling options. This research work is aimed at investigating the technological feasibility of using MF waste as a filler material in concrete. The ultimate objective is to produce lighter-weight concrete with enhanced engineering properties as an effective approach to protecting the environment from MF solid waste.

## CONCRETE

The undertaken research work is concerned with the reuse of MF in producing concrete with enhanced characteristics. Thus it is appropriate to review relevant concrete characteristics to understand the influence of MF on its properties.

The oldest concrete so far discovered dates from the Stone Age, around 7000 BC, and was found in 1985 in Southern Galilee, Palestine. The discovered concrete was made by burning limestone [5]. Today, concrete is a composite material made with crushed rock or gravel and sand (aggregate or filler) embedded in a hard matrix of Portland cement paste (binder). Admixtures are often added to concrete to obtain certain characteristics of concrete in its fresh or hardened states. Concrete has many advantages including ease and speed of construction, abundance of constituent materials, high toughness and strength, durability, and fire resistance. On the other hand, concrete also has some limitations, including low strength-to-weight ratio, low tensile strength, moderate thermal insulation, brittleness, volume instability, and deterioration due to environmental factors.

### Portland Cement

Portland cement is the product obtained by intimately mixing together calcareous and argillaceous or other alumina, silica and iron oxide-bearing materials, burning them at a clinkering temperature and grinding the resulting clinker [6]. The compound composition of Portland cement includes tri-calcium silicate ($C_3S$), di-calcium silicate

($C_2S$), tri-calcium aluminates ($C_3A$), tetra-calcium alumina ferrite ($C_4AF$) and calcium sulfate dehydrate ($C\hat{S}H_2$).

Hydration of Portland cement involves chemical and physical processes between water and cement that influence the characteristics of the hardened concrete. These reactions liberate heat and require time to reach full hydration. The reactions result in an increase in solid volume on the expense of water volume. Calcium silicate hydrates to produce $C_3S_2H_3$ (C-S-H) and calcium hydroxide (CH). C-S-H is a poor crystalline material comprising 1/2 to 2/3 of the volume of the cement paste, and thus dominates its behavior and contributes to its strength. The C-S-H grows in the available space within the paste, which was originally occupied by water, and stops growing in a particular direction when it meets an obstacle. Calcium hydroxide is a well crystalline material comprising 20 to 25% of the cement paste volume. The calcium hydroxide grows within the capillary pore space and stops growing in a particular direction when it faces an obstacle. $C_3A$ and $C_4AF$ hydrate to produce ettringite. Ettringite comprises 10 to 15% of the cement paste volume and grows into the capillary pores between the cement grains. In the first stage of hydration where the paste has not yet hardened, ettringite makes space by pushing aside the cement grains. After the paste has gained rigidity, the extra space necessary for continued formation of ettringite is created by expanding the total volume of the paste. Ettringite crystals will make space for themselves when they are impeded by solid material, which may develop high crystal growth pressures causing internal cracking in the cement paste. It is known that $C_3A$ hydrates more rapidly than other compounds, however, the presence of gypsum reduces the rate of early hydration for this compound. $C_3S$ compound (alite) also hydrates quickly, but slower than $C_3A$. The rate of hydration of $C_2S$ (belite) is the slowest. $C_4AF$ (ferrite) hydrates slower than the alite. $C_3S$ is responsible for the early strength of Portland cement; the contribution of $C_2S$ to the strength is obtained at a later stage. Thus, the calcium silicates provide most of the developed strength.

The strength of concrete is influenced by the strength of hydration products and the bond strength between the cement paste and the aggregate particles (fillers). The reuse of MF waste as a filler material is expected to influence the bond strength but its influence on the strength of the hydration product is expected to be less significant.

## Insulation Characteristics

The resistance of a material to the transfer of heat depends on its composition and physical characteristics. The specific resistance (R) of any material varies with its thickness. For economical purposes, construction practice limits the thickness of materials to the minimum required to achieve acceptable safety. The insulation characteristic of concrete is of great importance to control the loss of heat from buildings in winter and the gain of heat in summer. Conversely the amount of heat that will be conducted by that material decreases as thickness increases. The conductivity (k) of a material is the amount of heat that will conduct through unit thickness per unit area of material. The conductance (C) is the amount of heat that will conduct through one unit surface area per unit of thickness. The actual heat loss through a structure such as a wall or a floor is measured in British Thermal Units (BTU). One BTU is the amount of heat needed to raise the temperature of one pound of water one degree Fahrenheit. The heat loss in BTU's through a given structure is determined by calculating the total conductance (U) of that structure. The U value of a structure is the number of BTU's per hour that will flow through one-square foot of the structure when there is a one-degree difference in temperature between the two sides. The higher the U value of a structure, the more heat will be lost, and the lower the U value, the less heat will pass and the better its insulation properties.

The conductivity of materials varies with their density. Construction materials such as concrete have lower conductivity than the metals but will still conduct considerable heat. In the undertaken research work the new composite material of MF and concrete is expected to have good thermal insulation, since MF itself has good thermal insulation properties.



## MELAMINE FORMALDEHYDE POLYMERS

Polymeric materials are used in almost all areas of daily life. The biggest group of polymeric materials is plastics. It accounts for over 78% of production, while synthetic fibers account for 14% and elastomers for 7.4% [7]. Polymers can be divided into two major types based on their thermal behavior. The first type is the thermoplastics, including high- and low-density polyethylene, polypropylene, poly vinyl chloride and polyesters. Thermoplastics can be heat-softened, and thus can be used again. The second type is the thermoset plastics, which include phenol formaldehyde, urea formaldehyde and melamine formaldehyde resins, unsaturated polyesters and epoxy resins. Thermoset plastics cannot be heat-softened and thus cannot be recycled because of the formation of chemical crosslinks by covalent bonds. The solid waste problem of thermosetting plastic is greater than thermoplastics because once shaped into permanent form it cannot be

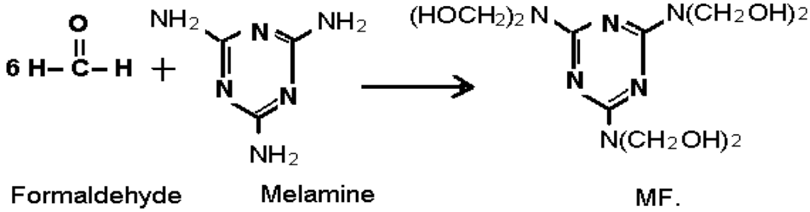


**FIGURE 1** Formation of melamine-formaldehyde (MF).

re-melted or reshaped. In this respect the raw material is converted to a hard, insoluble and infusible substance. Thermoset plastics consist of molecules with permanent crosslinks between linear chains that form a rigid three-dimensional network structure, which cannot flow.

MF is produced by the condensation reaction of an aldehyde and a compound containing an amino group (NH2). The formation of MF occurs when melamine is heated with formaldehyde at temperatures between 80–100°C, as shown in Figure 1 [8].

In a typical process, MF molding powders are generally prepared from as aqueous syrup containing resin with MF; the molar ratio of resin to filler is 2 to 1. This is compounded with fillers, pigment, lubricants, stabilizers, and in some cases, with accelerators in a dough-type mixer. For the more common decorative molding powders, cellulose is used as filler. A small amount of bleached wood flour is sometimes added to reduce shrinkage and cracks near inserts. Industrial grade materials employ fillers such as silica and glass fiber. These are incorporated by dry-blending methods. Molding temperatures are usually in the range of 145 to 165°C and molding pressure varies from 30 to 60 MPa [8]. The MF is used in producing tableware, largely because of their wide color range surface hardness and stain resistance. Cellulose-filled compositions are also used for making trays, clock cases, radio cabinets and other applications. The mineral-filled powders are used in making electrical appliances, knobs and handles for kitchen utensils. Formica™ and Ware Rite™ decorative laminates in which the surface layer is impregnated with MF and phenol resins. Glass-reinforced MF laminates are valuable because of their good heat resistance (they can be used at temperatures up to 200°C) coupled with good electrical insulation properties in addition to their resistance to cracking. The MF resins are widely used as hot-setting adhesives; they are also useful in textile finishing. For example, they are useful agents for permanent glazing, rot-proofing, wool-shrinkage control and in conjunction with phosphorus compounds as flame retardants [9]. The limitations of MF include its fair

**TABLE 1** Melamine-Formaldehyde Characteristics

| Property | MF (cellulose-filler) |
|---|---|
| Specific gravity | 1.47 to 1.52 |
| Tensile strength, Mpa | 34.5 to 89.7 |
| Elongation, % | 0.6 to 1.0 |
| Compressive strength, Mpa | 138 to 310.5 |
| Thermal conductivity (cal./cm.s. °C) $10^{-4}$ | 6.5 to 10 |
| Specific heat, cal./gm.k | 0.4 |
| Water absorption percent | 0.1 to 0.6 |
| Solvent hydrocarbon | None |

dimensional stability and low-impact strength [10]. Table 1 shows the relevant physical, mechanical and thermal characteristics of MF [7,11].



## Polymers in Concrete

Polymers such as unsaturated polyester have been used in concrete as adhesives [12]. The cost of such adhesives is high compared to Portland cement concrete [13]. Polymers such as polypropylene fibers have also been used as inert fillers in making concrete with good blast resistance [14–16]. The disadvantage of such concrete is that a fire will increase the porosity of concrete. In addition the polypropylene fibers have a low elastic modulus and poor physicochemical bonding with cement paste [17].

In this work MF waste is intended to be reused in concrete as a filler material to partially replace the fine aggregate (sand).

# EXPERIMENTAL

## General Description of Test Program

In the test program, MF waste from the industry was ground to particle sizes comparable to those of sand. The test program included tests on mortar (mixture of cement, fine aggregate (sand) and water) and on concrete (mixture of mortar and coarse aggregate). Various percentages of sand were replaced by MF. The replacement percentages varied from 0% to 60% by volume with 10% increments. It should be mentioned that testing of mortar was included because certain specifications require that the tests be carried out on mortars, and some of the properties, such as direct tensile strength, can not be performed on concrete due to gripping problems. In addition, there are some practical applications, such as plastering and bricklaying, which are based on the use of mortar. The tests on mortar included compressive and tensile strengths, density and thermal insulation. The tests on concrete included compressive strength and density. In addition, tests were also carried out to obtain basic properties of the constituent materials. The testing variables included the sand replacement percentages (MF%) and the water-to-cement ratio (w/c). It is known that concrete's properties vary in accordance with the way it is tested and by changes in the properties of its constituent materials. To obtain comparable results, the material used in all test specimens was taken from the same source and their properties were maintained throughout the test program. In addition, standard testing procedures in accordance with either ASTM or BS, depending on the availability of equipment and applicability of tests, were followed. However, for comparison purposes the same standard was used for each test type.

The properties of the aggregates, including the MF, were determined by performing relevant tests including the sieve analysis (ASTM Method C136), specific gravity (ASTM C128), dry density (ASTM D1556) and surface texture (using three-dimensional microscope).

## Gradation of MF and Aggregates

Standard sieves ranging from sieve No. 4 (4.75 mm) to sieve No. 100 (0.15 mm) were used to obtain the grading of fine aggregates (sand) and MF (since MF was used as a sand replacement). The sieves for the coarse aggregate ranged from 19.0 mm to 2.38 mm. Two sieve analysis tests for each material were carried out and their average results were considered. The gradations obtained are shown in Table 2. Based on BS 882 the gradations indicated that the sand

**TABLE 2** Sieve Analysis for Sand and MF

| Sieve size | Sand % passing | MF % passing | Coarse aggregates % passing |
|---|---|---|---|
| 19.00 mm | – | – | 100 |
| 9.52 mm | – | – | 96 |
| 6.7 mm | – | – | 62 |
| No. 4 (4.76 mm) | 100 | 100 | 42 |
| No. 8 (2.40 mm) | 100 | 100 | 4 |
| No. 16 (1.20 mm) | 100 | 77 | 0 |
| No. 30 (600 μm) | 92 | 43 | – |
| No. 50 (300 μm) | 31 | 29 | – |
| No. 100 (150 μm) | 0 | 18 | – |
| No. 200 (75 μm) | – | 11 | – |

was fine and the MF was fine to medium, with better grain size distribution than the sand. The uniformity of sand and MF were also determined by calculating their fineness modulus (FM). The FM for sand and for MF was equal to 1.8 and 2.3, respectively, which indicated that sand was fine and may adversely influenced the properties of concrete.

## Physical Properties of Sand and MF

The measured specific gravity for sand was equal to 2.84, which compares well with that for fine sand (2.8) [18]. The measured specific gravity for MF was equal to 1.57. The dry densities for MF and sand were measured with free fall of the materials into a cylinder of specific volume and also by pressing the materials inside the cylinder. The free fall densities of sand and MF were equal to 1.50 g/cm$^3$ and 0.78 g/cm$^3$, respectively. The pressed densities of sand and MF were equal to 1.69 g/cm$^3$ and 0.98 g/cm$^3$, respectively.



## Compressive Strength of Mortar

The compressive strength tests on mortar were carried out using 70.7 mm cube specimens. After 24 h of casting, the specimens were immersed in saturated lime water at lab temperatures which varied between 15°C and 20°C until testing after 28 days. A load was applied continuously to the specimens until crushing or until the load was dropped significantly. For each test the compressive strength was obtained from three cubes considering their average strengths. The tests were carried out on mortars with w/c ratios of 0.43 and 0.45. The MF percentages varied between 10% and 60%. The gradation of MF was similar to that of sand gradation which varied between sieve No. 4 and No. 100. The batching quantities used in these tests are shown in Table 3 and the measured mortar compressive

**TABLE 3** Batch Quantities for Mortar Compressive Strength

| Specimen* | MF (%) | Water (gm) | Cement (gm) | Sand (gm) | MF (gm) |
|---|---|---|---|---|---|
| 1 | 0 | 83 for w/c = 0.43 | 192 | 575 | 0 |
| 2 | 10 | and | | 517 | 31.8 |
| 3 | 20 | 86 for w/c = 0.45 | | 460 | 63.8 |
| 4 | 30 | | | 402.5 | 95.3 |
| 5 | 40 | | | 345 | 127.2 |
| 6 | 50 | | | 287.5 | 159 |
| 7 | 60 | | | 230.3 | 190.7 |

*For each w/c ratio there were 7 specimens and each specimen included three cubes, i.e., the total number of tested cubes was 42.

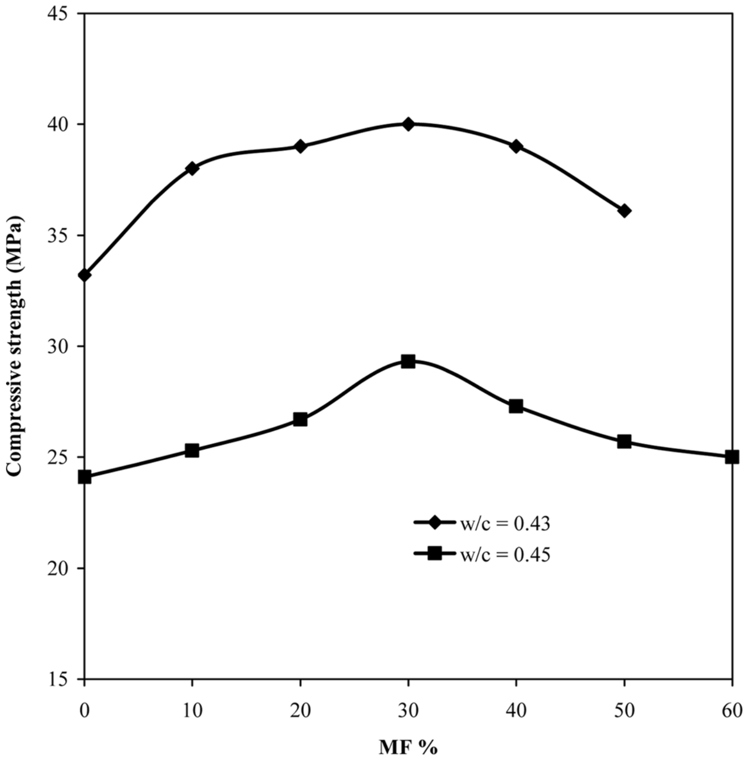


**FIGURE 2** Mortar compressive strength.



strengths for the two w/c ratios are shown in Figure 2 for the various MF percentages.

## Tensile Strength of Mortar

Direct tension tests on mortars were carried out using dumbbell (dog-bone) shape specimens of 25 mm $\times$ 20 mm cross-section. The specimens were prepared and tested in accordance with ASTM C190. The tests were carried out on mortars having the same constituent proportions and MF percentages that were used for mortar compressive strength tests detailed in Table 3 with w/c ratio equal to 0.45. The specimens were pulled away in the tensile testing machine from the two sides until broken. The measured tensile strengths of mortars are shown in Figure 3 for the various MF percentages.

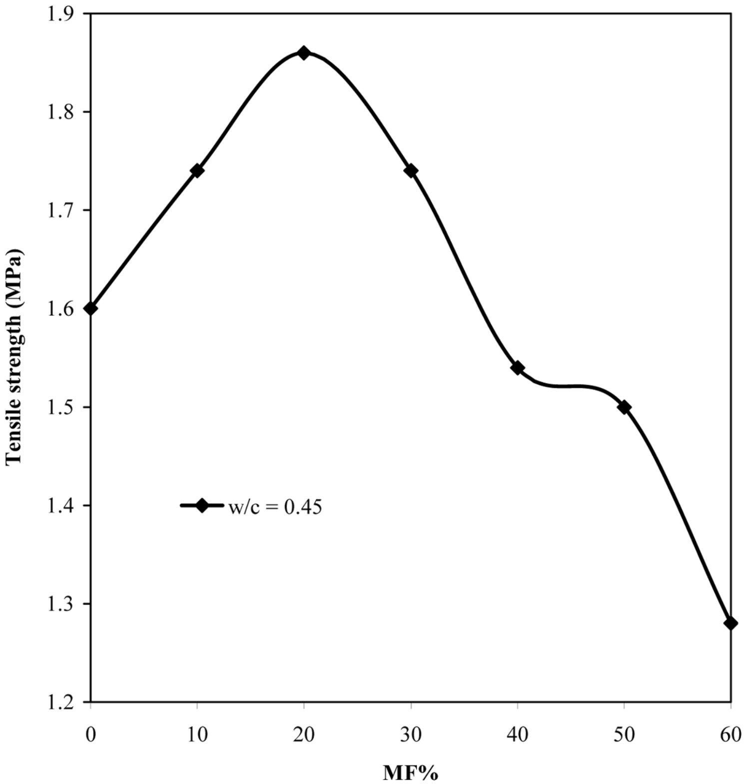


**FIGURE 3** Mortar tensile strength.



## Thermal Insulation of Mortar

The tests for the evaluation of the thermal insulation characteristics were carried out on mortar cubes having the same constituent proportions and varied MF percentages (0, 20, 40 and 60%) that were used for mortar compressive strength tests with w/c ratio equal to 0.45, detailed in Table 3. The specimens were left in the laboratory under ambient conditions for 24 h after casting, then were immersed in water for one week. The specimens were then removed from water and left in the laboratory under ambient conditions for another week until testing. The heat insulation characteristics of mortar were evaluated by comparing the heat transfer in one direction through specimens having various MF percentages. A hot plate was the source of heat which was placed direct to one side of the specimen. The heat transfer was measured at a fixed time using three thermometers inserted in holes drilled inside one of the specimen faces as shown in Figure 4. To

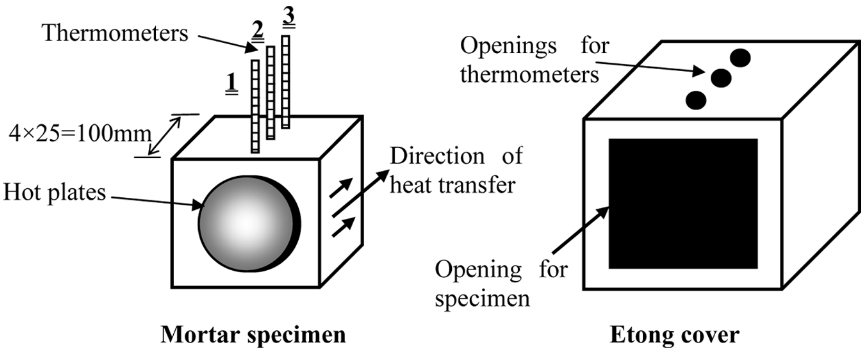


**FIGURE 4** Arrangements for thermal insulation test.

ensure the same testing conditions, the specimens were placed inside a box of Etong block (lightweight commercial insulating blocks). Three thermometers were placed in the holes and then the plate was heated to 250°C. The average heat transfers measured through mortar specimens by the three thermometers are shown in Figure 5 for the various percentages of MF.

## Compressive Strength of Concrete

Compressive strength is the single most important test for concrete since the obtained strength is directly used in structural design, and

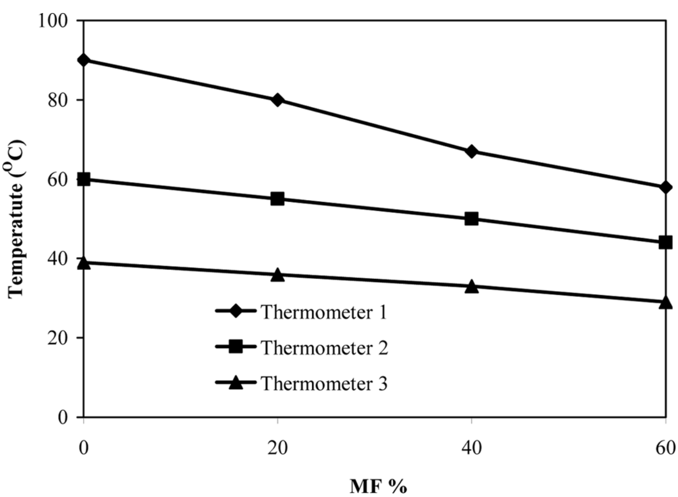


**FIGURE 5** Thermal insulation characteristics.

**TABLE 4** Batch Quantities for Concrete Compressive Strength

| Specimen* | % of MF | Water (gm) | Cement (gm) | C. aggregate (gm) | Sand (gm) | MF (gm) |
|---|---|---|---|---|---|---|
| 1 | 0 | 193 for w/c = 0.55, | 344 | 1377 | 688 | 0 |
| 2 | 10 | 206 for w/c = 0.6 | | | 619 | 38 |
| 3 | 20 | and | | | 550 | 76 |
| 4 | 30 | 234 for w/c = 0.65 | | | 482 | 114 |
| 5 | 40 | | | | 413 | 152 |
| 6 | 50 | | | | 344 | 190 |
| 7 | 60 | | | | 275 | 230 |

*For each w/c ratio were there 7 specimens and each specimen included three cubes, i.e., the total number of test cubes was 63.

other mechanical properties of concrete such as elastic modulus and tension strength can be estimated based on concrete compressive strength. In these tests the compressive strengths were obtained using 100 mm concrete cubes. The curing conditions and testing variables were similar to those of compressive mortar tests except that three w/c ratios equal to 0.55, 0.60, and 0.65 were used as detailed in Table 4. The measured concrete compressive strengths for the three w/c ratios are shown in Fig. 6 for the various MF replacement percentages.



### Densities of Mortar and Concrete

The measured average density values for mortar and concrete specimens are shown in Figure 7 for the various MF percentages.

## RESULTS AND DISCUSSION

### Strengths

Strengths of concrete and mortars are influenced by many factors, including w/c ratio, time, cement type and content, aggregate size and gradation, curing condition, testing procedure and the use of admixtures. The test results in Figures 2, 3 and 6 show the advantageous influence of partially replacing sand with MF on the strengths of mortar and concrete specimens made with various w/c ratios. The curves in these figures consist of two parts; one is ascending and the other is descending. In comparison with the corresponding control specimens without MF, the figures show that both the tensile and compressive strengths increased as MF percentages were increased

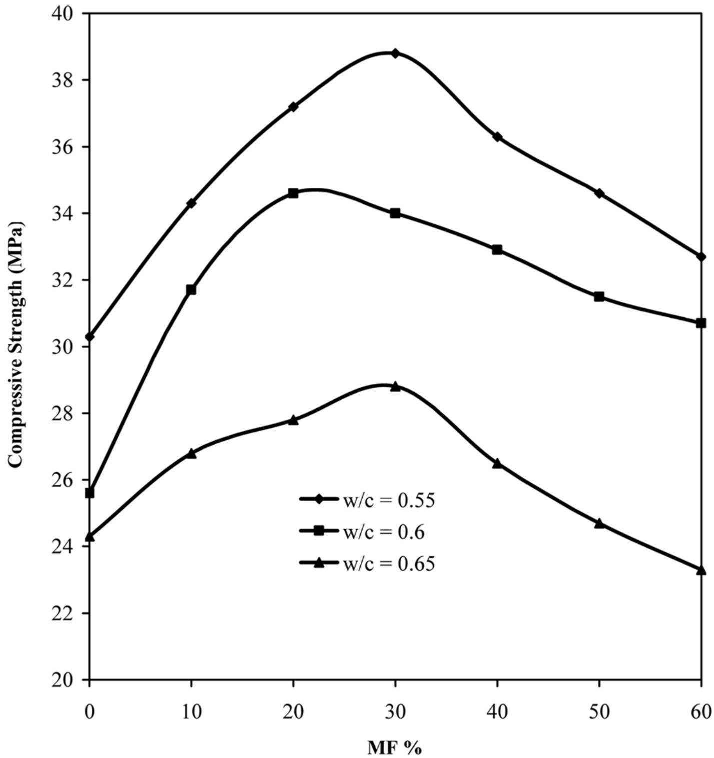


**FIGURE 6** Concrete compressive strength.



from 0% to about 30%. Then with increasing the MF percentages, the strengths were decreased to reach minimum values at 60% MF. However, the obtained minimum compressive strengths for mortar and concrete were at the same strength level compared to their control specimens without MF, as shown in Figures 2 and 6. The measured increase in the mortar compressive strength ranged from 20% for $w/c = 0.45$ to 22% for $w/c = 0.43$ compared to their control specimens without MF. In the case of concrete, the increase in the compressive strength ranged from 19% for $w/c = 0.65$ to 43% for $w/c = 0.6$. The test results showed that MF has a more pronounced influence on mortar and concrete strengths with low w/c ratios. This may be attributed to the fact that at lower w/c ratios it is easier to obtain high strength, thus the enhancement in aggregate characteristics by the use of MF would significantly increase the strength.

One of the limitations of concrete is its weak tensile strength. The direct tensile strength test was done on mortar since there is no such

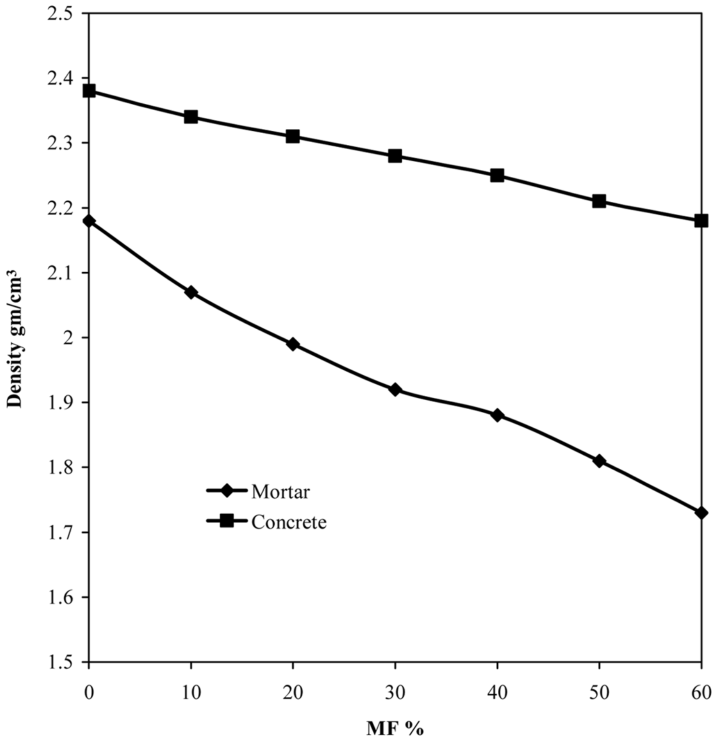


**FIGURE 7** Densities of mortar and concrete.



test for concrete. The measured increase in the mortar tensile strength reached up to 16% compared to that of control specimens without MF. This would be considered a significant advantage for concrete, in which tensile strength is utilized in the design, such as in the case of uncracked sections considered in the design of liquid-retaining structures. The enhanced tensile strength will also improve the shear resistance of structural concrete members [19,20].

The resulting similarity in the structural behavior of mortar and concrete is expected since the concrete is made by adding coarse aggregate to the mortar. Failure surface in concrete normally passes through the mortar matrix and at its interface with the coarse aggregates. Thus it is influenced mainly by the mortar strength, the characteristics of the fine aggregates and the bond strength at the interface of the coarse aggregates. Based on this understanding the significant influence of MF replacement on the strength may be attributed to the following factors:

## Size and Gradation of Sand and MF

Normally, aggregates comprise 70% to 80% of concrete volume. In order to obtain concrete of good quality in terms of strength and durability with minimum cost, the aggregates should be well-graded. The MF particles used in the test specimens were fine to medium with better gradation (FM = 2.3) compared to the replaced sand which was fine (FM = 1.8). A combination of the two aggregates, i.e., sand and MF, has resulted in a better gradation which contributed to the increased strength. It seems that an optimum gradation has been obtained at about 30% MF replacement which corresponded to the obtained higher strength. The increase in the compressive strength in the case of concrete (up to 43%) was higher than that for mortar (up to 22%). This may be attributed to the better gradation of aggregates (coarse aggregate, sand and MF) in the case of concrete which had a wider range of particle sizes. As the w/c ratio increased, a weaker bond would have developed at the interface of coarse aggregates, which explains why concrete with a lower w/c ratio achieved less of an increase in compressive strength (19%).

## Shape and Texture of Sand and MF

The shape and texture of aggregates influence the mechanical properties of concrete thus they should be considered in the petrographical determination of concrete [21]. The use of smooth particles of round shape is the best for achieving high workability of concrete since they require minimum lubrication that is provided by the cement paste. However, the interfacial bond between aggregates and paste is reduced and in turn the concrete strength is also reduced. Angular particles have higher surface area to volume ratio and thus require more paste to coat them. Angular particles with rough surface texture provide more surfaces and thus result in increased bond strengths. Highly irregular particles with sharp edges and rough surface texture result in greater inter-particle interactions during mixing and handling. Such particles may also result in large internal stress concentrations that may lead to bond failures. The MF particles, which were used in the test program, had irregular semi-angular shape with a relatively smooth surface texture that did not require large amounts of cement paste for coating and in the same time provided good bond strength. It should be mentioned that the workability of concrete was not measured, however, it was noticed that concrete had a higher workability level as MF was increased, which allowed better compaction of concrete and contributed to the enhanced strength. The sand particles were of angular shape with smooth surface texture that naturally disintegrated from rock and subjected to weathering. A combination of sand and MF resulted in particles that possessed preferable shape and texture characteristics that seemed to contribute to the increased strength especially at about 30% FM.

### Strengths of Sand and MF

The compressive strength of cellulose-filled MF ranges from 138 to 310.5 MPa (ASTM D-695). The flexural yield strength ranges from 62.1 to 158.7 MPa (ASTM D-790). The hardness measured by Rockwell test ranges from M110 to M125 (ASTM D-785). Thus MF is classified as a strong material when compared with other plastics. On the other hand the strength of stone aggregates is influenced by the type of rock they originally disintegrated from. In general the sand may have a slightly higher compressive strength than MF. The test results shown in Figures 2, 3 and 6 showed improvements in the strengths of mortar and concrete, despite the strength of MF being lower than that of sand. It seems that with increasing the MF percentage from zero to about 30, the enhancement in strength due to the resulting combined gradation, shape and texture of the sand and MF was more significant than the possible adverse influence due to the lower strength of MF. As the MF percentage increased above the value of 30%, the strength starts to decrease since large amount of MF is used to replace the stronger sand, however, the strengths of mortar and concrete were still higher than those without MF due to the other factors related to gradation, shape and texture. With increasing MF percentages the strengths of mortar and concrete will continue to decrease until they reach lower values than those of the control specimens without MF due to a combination of the adverse influencing factors, i.e., gradation, shape, texture and strength of sand and MF materials. Therefore, in practice there should be an identified limit concerning the maximum allowable replacement percentage of MF depending on the type of constituent materials used. In this regard in practice, trial mixes should be carried out to determine appropriate limits.

### Chemical Composition

To date, the exact nature of the paste aggregate bond is not fully understood [22]. In general aggregates are inert materials, with the exception of some aggregates that react with alkalis. However, to some extent the chemical composition of the aggregate does affect bond strength and in some cases the properties of the layer at the paste-aggregate interface. This, in turn, suggests that a chemical reaction may take place at the interface. Such a reaction may explain the dependence of bond strength and the associated concrete strength on the chemical composition of the aggregate [22]. The bond is characterized by the presence of a thin layer which bridges the aggregate with the paste. This layer is formed as a result of a chemical reaction between the cement and the aggregate, or of epiaxial growth, or a combination of both. Therefore, it is possible that a chemical reaction may have taken place between the cement paste and the MF particles which could have contributed to the enhancement in the obtained strength.

## Density

Another limitation of concrete is its heavy weight, or more correctly its low strength/weight ratio. A decrease in the density of mortar up to 21% was obtained with 60% MF compared to control specimens without MF, as shown in Figure 7. The figure also showed a corresponding decrease in the density in percentage of concrete equal to 8.5% due to the presence of coarse aggregates. For concrete at $w/c = 0.06$ the strength/weight ratio ranged from 10.76 to 15.85 ($MPa/gm/cm^3$) for concrete without MF and with approximately 30% MF replacement respectively as can be deduced from Figures 6 and 7. Thus the enhancement in this ratio reached up 47% for this concrete. This showed the significant influence of using MF in overcoming the limitations of concrete. Such concrete would have great practical applications since it will allow a decrease in the size of structural concrete elements resulting in a more economical and efficient structures.

## Thermal Insulation

The test results for the evaluation of the thermal insulation characteristics shown in Figure 5 have demonstrated the advantageous influence of replacing sand by MF. The thermal insulation was increased as the percentage of MF was increased from 0% to 60%. The temperatures of concrete along the direction of the heat transfer was measured by the three thermometers placed successively, as shown in Figure 4. The temperatures were lower for specimens with increased MF percentages. A drop in temperature up to 30% was recorded by thermometer 1 located near the heat source as shown in Figure 7 for specimens with 60% MF. At 30% MF the drop in temperature reached up to about 15%. The improvements in the thermal insulation properties of the specimens with large amount of MF may by attributed to the lower thermal conductivity of MF which normally ranges from 0.27 to 0.42 W/m.°C compared to that for sand which is equal to 1.4 W/m.°C as given in Table 1. The lower specific gravity of MF, which is equal to

1.5 compared to that for the sand, which is equal to 2.6, may also have contributed to the enhanced thermal insulation characteristics for specimens with increased MF percentages [23].

## CONCLUSIONS

1. It was possible to reuse melamine formaldehyde (MF) solid waste to produce mortar and concrete with enhanced characteristics. The MF waste from the industry was ground to size and gradation similar to that of fine aggregates (sand). The MF has been used to partially replace the sand with various percentages ranging from 0% to 60% by volume. The specimens without MF, i.e., 0% replacement were used as control specimens for comparison purposes. The tests included compressive strength of mortar and concrete, tensile strength of mortar and thermal insulation of mortar. Other physical characteristics such as densities of concrete and mortar, particle characteristics of MF and aggregates were also measured.
2. The level of strength enhancement obtained in the test specimens was controlled by the properties of the materials, which were used in the test program. In practice it is necessary to carry out trial mixes to determine the corresponding enhancement level for the available materials.
3. In general the compressive strengths of concrete and mortar were increased as the percentage of MF was increased to reach maximum values at approximately 30% MF. With further increase in MF percentage the strength was reduced. However, up to 60% MF the obtained strength was at the same level compared to control specimens without MF. The maximum increase in strength was achieved at percentage of MF 43%. This was obtained in concrete specimens with $w/c = 0.6$.
4. A decrease in the density of mortar up to 21% was obtained with 60% MF. The corresponding decrease in the density of concrete was equal to 8.5%.
5. The strength/weight ratio increased by up to 47% for concrete with 30% MF compared to that without MF. This shows the significant influence of using MF in overcoming the limitations of concrete. This particular concrete would have great practical applications since it will allow a decrease in the size of structural concrete elements thus producing more economical and efficient structures.
6. The tensile strength of mortar was increased and reached up to 16% compared to that of control specimens without MF.

7. The obtained increase in strengths of concrete and mortar may be attributed to the enhancing characteristics of MF particles related to type, size, gradation, shape, texture and strength.
8. The thermal insulation characteristics of mortar were increased as the MF percentage was increased from 0% to 60%. A drop in samples temperature up to 30% was recorded in specimens with 60% MF compared to that of control specimens without MF. The improvements in the thermal insulation properties of the specimens with larger percentages of MF may be attributed to the lower thermal conductivity and specific gravity of MF compared to those of replaced sand.

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